Arnold Schwarzenegger
Governor

CARBON SUPPLY FROM CHANGES IN MANAGEMENT OF FOREST, RANGE, AND AGRICULTURAL LANDS OF CALIFORNIA

PIER FINAL PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the Measurement, Classification, and Quantification of Carbon Market Opportunities in the U.S.: California Component project, contract number 100-98-001, conducted by Winrock International. The report is entitled *Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California.* This project contributes to the PIER Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Commission's Web site www.energy.ca.gov/pier/reports.html or contract the Commission at (916) 654-4628.

Table of Contents

Appendices

List of Figures

List of Tables

Abstract

The project described in *Carbon Supply for Forest, Range, and Agricultural Lands of California* was a portion of the Baseline, Classification, Quantification, and Measurement for Carbon Market Opportunities in California project. This project estimated the quantity and cost of carbon storage opportunities in California and developed carbon supply curves for the most important classes of carbon sequestration activities in land-use change and forestry projects.

The research found that the cost of carbon sequestration from changing forest management practices is relatively high. No forest management project, regardless of length of project, can provide carbon sequestration at less than \$2.70/MTCO_2. The largest potential source of carbon from forest management is for lengthening rotation by five years, which can potentially provide 2.16 to 3.91 MMTCO_2 at a cost of less than \$13.60 per ton.

For afforestation of rangelands, longer durations produce lower cost carbon. Afforestation of rangelands provides the most carbon at the least cost (≤ \$2.7/MT CO_2)—about 33 MMTCO_2 at 20 years to 4.57 billion MTCO_2 at 80 years.

Conservation tillage (CT) seems to offer the greatest potential for producing carbon on agricultural land in California. It is estimated that California agricultural land could produce up to 3.9 MMTCO_2 /year through CT.

This report can help stakeholders more accurately estimate the quantity of carbon credits that might be available at different price points for different classes of projects. The estimates can help in preparation of a portfolio of potential stakeholder responses for a range of future climate scenarios.

Executive Summary

Objectives

The "Baseline, Classification, Quantification and Measurement for Carbon Market Opportunities in California" project began in 2002. One of the tasks is the estimation of the quantity and cost of carbon storage opportunities in California. The primary outputs from this task are carbon supply curves and corresponding maps for the most important classes of carbon sequestration activities in the land-use change and forestry sector.

Currently, the estimates of carbon sequestration potential most frequently cited are of the theoretical potential, without consideration of current land values and alternate uses. To fill this gap in knowledge, this report sets out to answer the basic question: "How many carbon credits would landowners offer for sale for a particular class of activity at various price points and where are these located?" The information contained in this report can help stakeholders prepare for an uncertain regulatory future by providing more accurate estimates of the quantity of carbon credits that might be available at different price points for different classes of projects. The estimates can help in preparation of a portfolio of potential stakeholder responses for a range of future climate scenarios.

Information about current land use (based on the California Department of Forestry (FRAP 2002), potential changes in land use and the incremental carbon resulting from the change, opportunity costs, conversion costs, annual maintenance costs, and measurement and monitoring costs were obtained and used in the analyses. The analyses are performed in a geographic information system (GIS) to include the diversity of land uses, rates of carbon sequestration, and costs. As a result, not only are more realistic estimates of the potential supply of carbon produced, but the use of GIS shows where the least to most expensive carbon credits will most likely be found. The general approach was to identify and locate classes of land where there is potential to change the use to a higher carbon content, estimate rates of carbon accumulation for each major potential land-use change activity for each land class, assign values to each contributing cost factor, and identify datasets and methods to estimate project risks.

Californian lands are classified into three main groups for the analyses presented here: forests, rangelands, and agricultural lands. Forests (about 23.7 million acres) include conifers, hardwoods, and mixed classes; rangelands (about 56.5 million acres) include a variety of non-woody (e.g., pasture, grasslands) and woody ecosystems (e.g., oak woodlands, chaparral); and agricultural lands (about 9.9 million acres) include a wide range of non-woody crops such as small grains, vegetables, and berries and woody crops such as vineyards and orchards.

The steps needed for estimating the carbon supply for a potential change in land use are:

1. Identify the classes of land uses and the associated changes in management that could lead to significant increase in carbon stocks
2. Estimate the area for each potential change in land use
3. Estimate the quantities of carbon per unit area that could be sequestered for the change in land use over a given time period

4. Estimate the total costs (opportunity, conversion, maintenance, and measuring and monitoring)
5. Combine the estimated quantities of carbon per unit area with the corresponding area and cost to produce estimates of the total quantity of carbon that can be sequestered for a given range of costs, in \$/metric ton C or \$/metric ton CO_2.

For forestlands, estimates of the potential carbon benefits were analyzed for four alternatives for 20 year and/or permanent contract periods: (1) allowing timber to age past economic maturity (lengthening rotation time); (2) increasing the riparian buffer zone by an additional 200 feet; (3) changing traditional clear cuts to group selection cuts, and (4) forest fuel reduction to reduce hazard of catastrophic fires, and subsequent use of biomass in power plants. For estimating the costs of allowing timber to age and the costs of enhanced riparian zone management, estimates are based on specific counties for public and private landowners, and then extrapolated to all counties throughout the state. For the group selection cuts, there appears to be little increased carbon sequestration in Sierran mixed conifers or coastal redwoods, but, these costs are provided to serve as an estimate of costs for other areas where a net increase in carbon stocks may occur.

For the fuel reduction alternative, the objective was to estimate the areas and carbon stocks of forests suitable for fuel reduction to reduce their fire risk and that were located within economic range of existing power plants for the high and very high fire risk forests. The analysis used a "Suitability for Potential Fuel Reduction (SPFR)" score on forest landscapes where significant carbon loss from wildland fires exist. Additionally, SPFR scores also ranked areas feasible for removing and transporting fuels to biomass power generating plants. The SPFR scores were created in a GIS using slope, distance to biomass plants, and distance from roads as equal weighted factors in the decision making process. Suitability scores for potential fuel reduction with highest suitability were assigned to areas with gentle grades of slope that are close to roads and biomass power plants. The analysis did not include the economic component due to the lack of a variety of data and resources needed to be confident about projections of carbon supply curves; but the analysis does present a first approximation of the potential reduction in carbon emissions if forest fuels were reduced.

For rangelands, estimates of the potential carbon benefits were analyzed for one alternative—afforestation. Historical evidence suggests that in many areas, large tracts of forest may have once stood where grazing lands now do. Moreover, a significant proportion of today's oak woodlands and annual grassland vegetation types on California's rangelands were also once either dense forests or similar woodlands but with significantly higher biomass than they currently contain. Presently, in much of the state, ranching is the primary activity on what remains of these lands that were once forests or woodlands. The general approach was to identify and locate existing rangelands where biophysical conditions could favor forests, estimate rates of carbon accumulation for the forest types projected to grow, and assign values to each contributing cost factor. The carbon supply is estimated for three time durations: 20 years, 40 years and 80 years of forest growth to reflect the impact of activity duration on the likely supply and to provide an assessment for the near–term and longer-term planning horizons.

For existing agricultural lands, only one major activity was analyzed –conservation tillage (CT) practices, which increases soil carbon up to a period of about 20 years maximum. Due to the high productivity and land values associated with California agriculture, the opportunity costs of displacing agricultural production with afforestation is not likely to be a valid source of carbon sequestration. Although CT has been proven to be a profitable management strategy for certain crops in many regions of the country, there are only very limited data regarding its application in California. Given the lack of research data and the great diversity of crops produced, it is essentially impossible to estimate the costs of CT adoption across the state in a meaningful way.

Outcomes

Although the whole range of costs and potential carbon available are presented in this report, Table S-1 summarizes the amount of carbon and the area available for several classes of opportunities at three price points: —≤ $13.6/ MT CO_2 ($50/MT C), ≤ $5.5/MT CO_2 ($20/MT C), and ≤$2.7/MT CO_2 ($10/MT C). Although California has substantial areas of forests, the cost of carbon sequestration from changing forest management practices is relatively high. No forest management project, regardless of length of project, can provide carbon sequestration at less than $2.70/MT$CO_2$ (**Table S-1**).

At a price of $13.6/ MT CO_2, the total amount of carbon that could be sequestered by afforesting grazing lands and changing forest management over a 20 year period is about 894 MMT CO_2 (Table S-1). Approximating this total amount to an annual rate, results in about 45 MMT CO_2/ yr. In comparison, the transportation sector emitted 160 MMT CO_2/ yr in 1999 and the electricity generation sector emitted about 57 MMT CO_2/ yr in 1999. Thus total sequestration at $13.6 per MT could offset about 79% of the electricity generating fossil fuel emissions and 28% of the transportation emissions.

Table S-1. Summary of the quantity of carbon (million metric tons CO_2 [MMT CO_2]) and area (million acres) available at selected price points—≤ $13.6/MT$CO_2$ ($50/MT C), ≤ $5.5/MT CO_2 ($20/MT C), and ≤$2.7/MT CO_2 ($10/MT C) —for several classes of activities on existing rangelands and forestlands over 20-year, 40-year, 80-year, and permanent (forest management—riparian buffer) durations.

Activity	Quantity of C—MMT CO_2			Area available—million acres		
	20 years	40 years	80 years	20 years	40 years	80 years
Forest management						
Lengthen rotation						
≤$13.6 (discounted C)	3.47	--	--	0.31	--	--
≤$13.6 (undiscounted C)	2.16	--	--	0.30	--	--
Increase riparian buffer-width						
≤$13.6		3.91 (permanent)			0.044	
Grazing lands						
Afforestation						
≤$13.6	887	3,256	5,639	12.03	17.79	20.76
≤$5.5	345	3,017	5,504	2.72	14.83	19.03
≤$2.7	33	1,610	4,569	0.20	5.68	13.34

The largest potential source of carbon from forest management is for lengthening rotation by five years that can potentially provide 2.16 to 3.91 $MMTCO_2$ at a cost of less than \$13.60/MT CO_2 depending on whether the carbon is undiscounted or discounted. Increasing the riparian buffer zone by 200 feet could sequester 3.91 $MMTCO_2$ permanently (assuming no catastrophic fire risk) at a cost between \$2.7 and \$13.6 per $MTCO_2$. This amount could occur on about 43,730 acres of forestland.

Lengthening forest rotation by five years shows that the counties with the least expensive carbon do not produce the highest quantities of carbon (**Figure S-1 and S-2**). The highest quantities of carbon that could be sequestered by this activity are located in the north coast counties, but these same counties have some of the most expensive carbon. The difference between the two discounted methods relates to different assumptions that could be used about the existing carbon in forest stands. Under method 1, shown in A and B in Figure S-1, carbon emissions in the initial harvest are ignored. Under the alternative accounting method, shown in C in Figure S-1, these initial emissions are considered. The costs tend to be lower for the alternative method of accounting because the emissions from the initial harvest are held off to future periods when rotations are extended, which creates an additional carbon benefit in early periods.

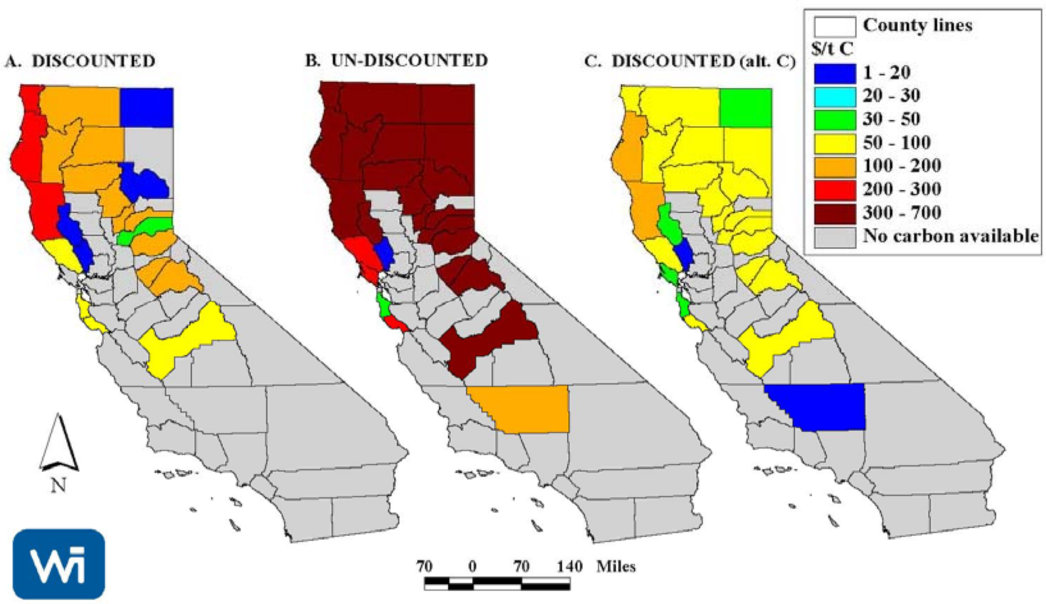

Figure S-1. Distribution, at the county scale, of the cost to sequester carbon (in \$/metric t C) via lengthening the forest rotation time by 5 years for two methods of discounting carbon (A. and C.) and for undiscounted carbon (B.).

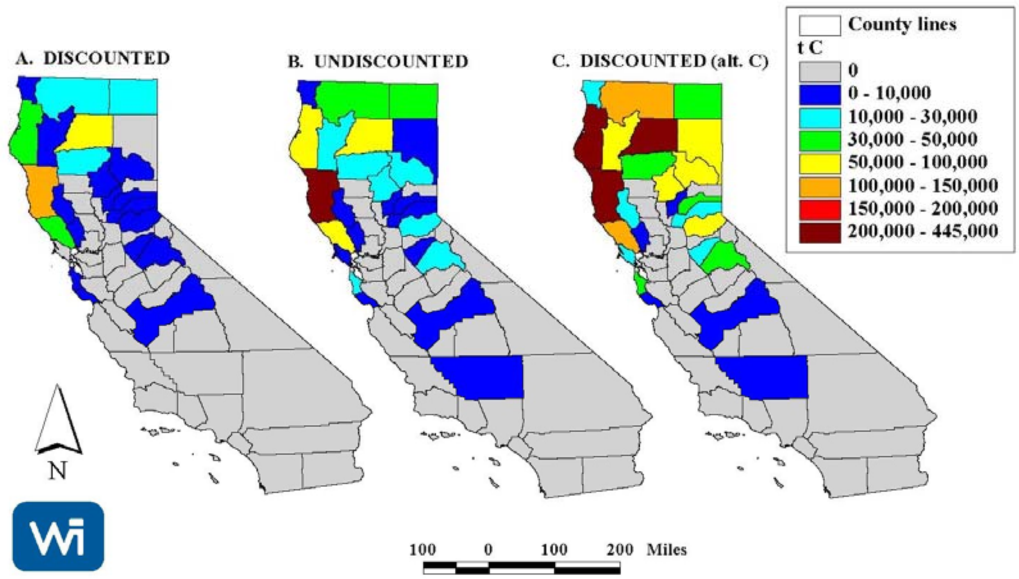

Figure S-2. Distribution, at the county scale of resolution, of the potential amount of carbon (metric t C) that could be sequestered on all forest lands by lengthening the forest rotation time by 5 years for two methods of discounting carbon (A. and C.) and for undiscounted carbon (B.).

Results are presented on public and on private lands of an analysis of the potential carbon sequestration and costs through expansion of the prohibitive riparian buffers for forestry operations. On public lands, the least expensive carbon, less than \$70/t C (or less than \$19/MTCO$_2$) generally coincides with those counties that potentially provide the highest quantities (Northeast Cascades and the northern part of North Sierra). On private lands, the trend is roughly the same, except that the most carbon at the least expensive cost is mainly centered in Northeast Cascade counties (**Figure S-3**). This project type could lead to leakage, because landowners could simply increase the overall size of the areas they propose to cut in order to compensate for the set-asides. The extent of this potential leakage has not been estimated here, but should be considered as part of carbon sequestration plans.

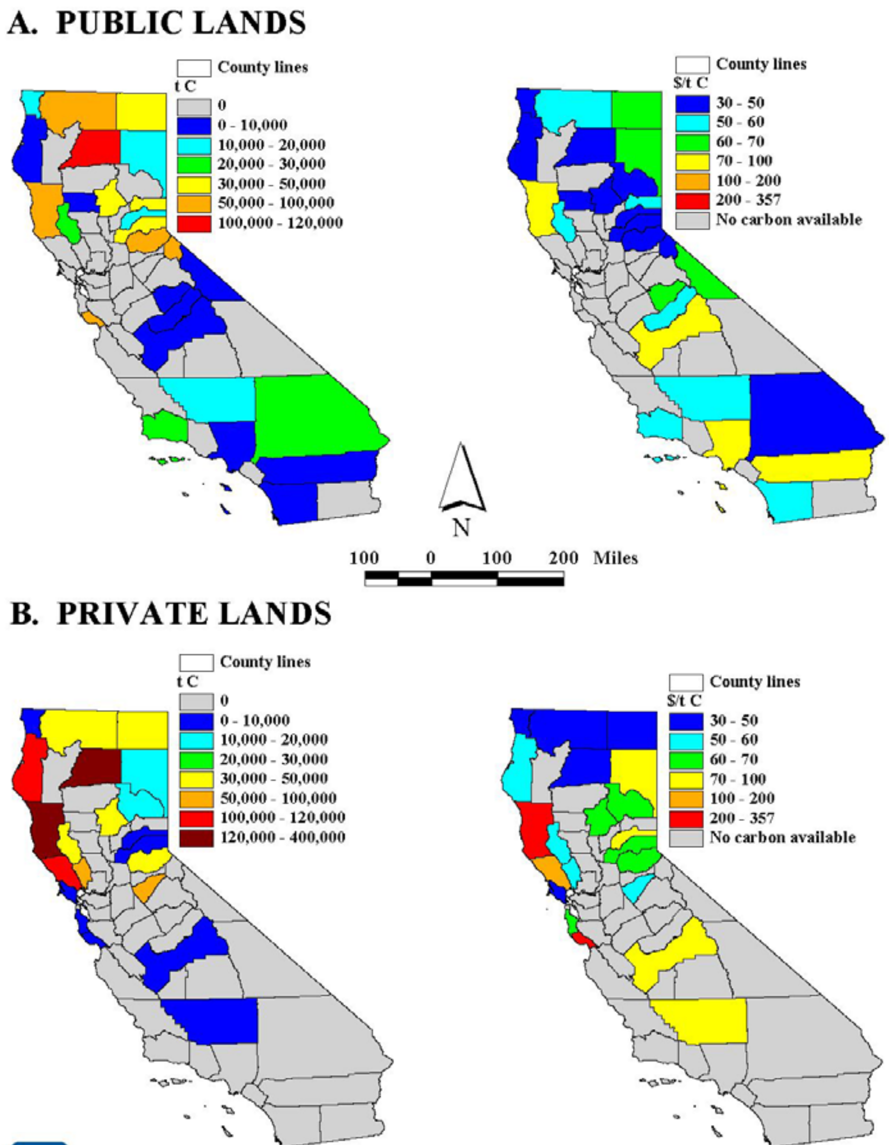

Figure S-3. Distribution, at the county scale of resolution, of the quantity (metric tons) and cost ($/metric t C) of sequestering carbon by extending riparian buffers 200 feet along perennial streams on public and private lands.

From the forest fuel reduction analysis, the area of forests in the upper 25% of the Suitability Potential for Fuel Reduction scores accounted for 774,827 hectares, areas that could be considered as suitable candidates for fuel reduction projects (**Figure S-4**). The forest area contained an estimated cumulative carbon stock of 74.2 MMT, and based on parallel work on California's baseline in the forestry sector, the estimated emissions from these forests if they burned could be as much as 23 million t C.

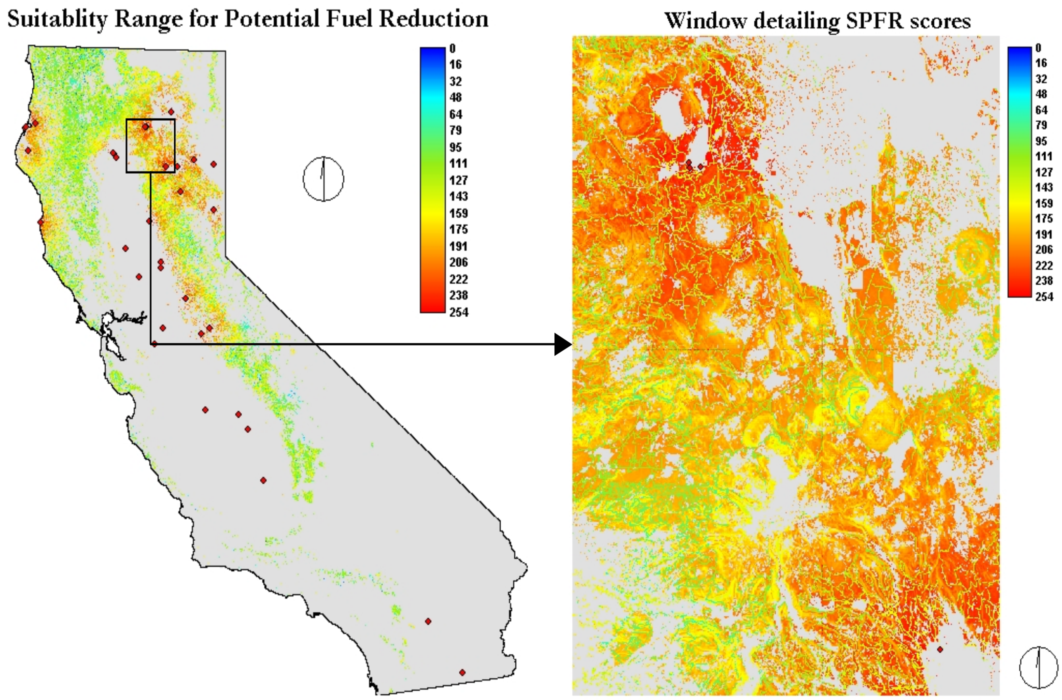

Figure S-4. Map of suitability potential for fuel reduction (SPFR) for California forests.

For afforestation of rangelands, longer durations clearly produce lower cost carbon but landowners may be more hesitant to commit land to projects of such duration (**Figure S-5**). Afforestation of rangelands (up to 13.34 million acres potentially available) provides the most carbon at the least cost (≤\$2.7/MT CO_2)—about 33 $MMTCO_2$ at 20 years to 4.57 billion $MTCO_2$ at 80 years (Table S-1). The counties with the least expensive carbon from afforesting rangelands are also the same counties that potentially can sequester the most.

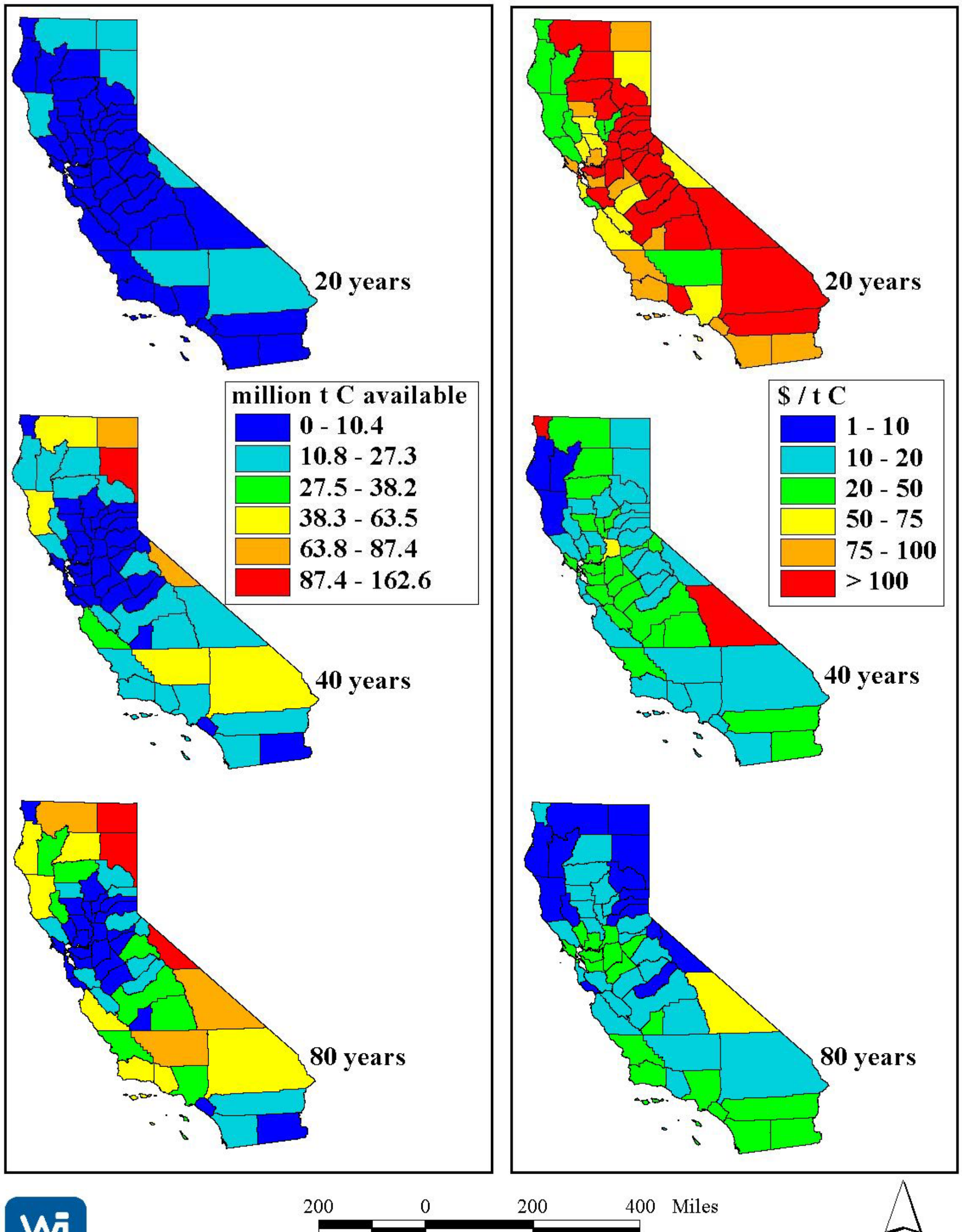

Figure S-5. Total carbon sequestered by afforestation of rangelands (metric tons; left) and area-weighted average cost per metric ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and after 20, 40, and 80 years.

The potential occurrence of fire is probably the largest risk to carbon sequestration by afforestation activities in California. Thus, in addition to the costs of physical management of the afforested areas, attention must be paid to the threat of fire to these investments. Because it is impossible to estimate what fuel loads will be present at a site after an afforestation activity, only the Fire Rotation Interval map (from CDF-FRAP) was used for the analysis. The majority of the potential areas for afforestation (49%) fall within the lowest risk category of fire rotation interval, and an additional 29% of the lands fall within the 100-300 year fire rotational interval. However, from a cost perspective, the 'High' to 'Very High' rotation intervals contain potentially some of the least costly carbon credits.

Of the possibilities for sequestering C on agricultural land in California, conservation tillage (CT) seems to offer the greatest potential. Based on a range of C sequestration rates of 0.35-0.61 MT/ha/year, it is estimated that California agricultural land could produce up to 3.9 $MMTCO_2$ /year through CT. The cost to sequester this amount of carbon is unknown for California, but in other regions of the United States this can incur little extra cost. However, it is unlikely that CT will be adopted on much of California's high-value and specialty crop land. The most likely crops for which CT will be adopted are tomatoes, cotton, beans, and corn, which do represent a large area of California agricultural land.

The vast majority of the potential soil carbon sequestration is located in the Sacramento and San Joaquin valleys in the central part of the state (**Figure S-6**). Additional smaller pockets can be seen in far northern and far southern counties, as well as along the central coast.

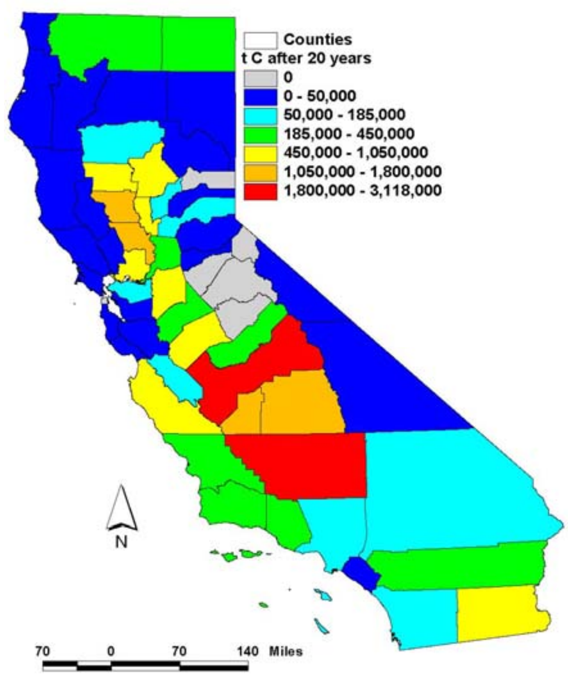

Figure S-6. Aggregated soil carbon sequestration estimates under conservation tillage regimes on row crops and small grains.

1.0 FORESTS

1.1. Introduction

According to the USDA Forest Service Forest Inventory and Analysis database (FIA), timberland in California encompasses approximately 7.2 million hectares. Of this land, 46% is softwood, 23% is hardwood, and the remainder is unclassified, chaparral, or unstocked. A large proportion of forests in California (58%) are owned by government agencies. While only 42% of California forests are owned privately, a disproportionate area of the most commercially important species are owned privately. For instance, 62% of Douglas fir, 69% of ponderosa pine, and 89% of redwood are owned by private landholders. These three species account for approximately 60% of total private timberland. Hardwoods constitute most of the remaining forests on private land, accounting for approximately 34% of private timberland area.

This section focuses on four alternatives for enhancing carbon sequestration in forests: (1) allowing timber to age past economic maturity; (2) enhancement of riparian zones; (3) group selection cuts, and (4) forest fuel reduction to reduce hazard of catastrophic fires, and subsequent use of biomass in power plants. For estimating the costs of allowing timber to age and the costs of enhanced riparian zone management, estimates are provided for specific counties for public and private landowners. For the group selection cuts, there is not enough information on potential increases in sequestration rates in different regions of the state, so these costs are generally to provide some information that can help policy makers or others as carbon sequestration information becomes available. For the fuel reduction alternative, this analysis is incomplete due to the lack of a variety of data and resources needed to be confident about projections of carbon supply curves. Calculating costs in this situation is more complicated—models need to be developed to estimate total costs related to collecting and transporting biomass fuel, and incorporating the potential market values of biomass fuels. However, by presenting the work to date, the approach is demonstrated and an indication of the amount of carbon that could potentially be conserved if fuel reduction measures were adopted in high fire prone areas is presented.

1.1.1. Discount Rates

Throughout this study, present value techniques are used. Present value techniques integrate the concept of the time value of money into economic decisions that occur over time. From the perspective of setting broad national policies for climate change, discounting is highly contentious because most of the benefits of climate change will occur far in the future and the costs occur sooner. Discounting weights these costs in decisions society makes today more heavily than the future benefits, even though the future benefits may be quite large. With respect to climate change, virtually any assumed positive discount rate makes most policy actions to avoid climate change (emissions targets, sequestration targets, etc.) look bad in a benefit cost test.

Most of the academic arguments about discounting revolve around determining how to equitably compare current costs with long-term benefits. Discounting causes policy makers to treat natural and human capital equally, such that investments in capital and technologies that might harm the environment are viewed more favorably in benefit cost tests with discounting, than without discounting. Thus, when evaluating policies that have long-term implications, positive discount rates will suggest that policies should be less stringent. In the context of climate change, positive discount rates suggest that current emissions reductions should be lower than if those same policies were evaluated without discount rates. It is currently unclear what rate of discounting should be used when evaluating climate policy, although many analyses use social discount rates ranging from 1%–4% at maximum. Most studies seem to use 3%.

The key issue in the academic and climate change literature has been one of considering how governments should use discount rates when evaluating national or state level policies. For individual companies evaluating specific projects to mitigate climate change either through energy abatement or through carbon offset projects, however, there should be little debate about discounting. Companies are vested with the fiduciary duty to achieve the maximum rate of return on investments for their shareholders. Discounting then, must be conducted under typical financial assumptions.

While it is imperative for companies to use discounting, the question of discounting for forest carbon projects has an additional layer of complexity, in that the rationale for discounting will also depend on the policies ultimately adopted for forest carbon offsets. If the rules for sequestration are set up so that companies can only offset future gains from carbon projects when the carbon gains for forest projects occur, then discounting future carbon flows should be used to correctly account for the timing of those flows. For example, forest carbon projects will provide annual flows of carbon each year forests grow, or rotations are extended. If only the annual gains can be counted against emissions in the year the gains occur, then companies should discount the carbon they believe they will get when they establish carbon projects.

The reason for this is simple. Companies have many current and future opportunities for abating emissions, including different projects than the ones considered here, abatement of their own energy emissions, or entirely new offset sources discovered or advanced in the future. Future costs for geological sequestration could drop precipitously in 2010, suggesting that companies should shift to that technology instead of forest offsets. Companies that fail to discount carbon flows when evaluating projects today do not adequately account for these other possibilities, and may consequently make unprofitable decisions today.

It is possible that society sets up a different set of rules and instead chooses to allow companies to count all projected, undiscounted future carbon gains from forest carbon projects against current emissions. Companies in that case would have fewer incentives to discount carbon in forest projects they develop today. Taking this step clearly would be risky for society, given that many things could happen to carbon projects that limit the actual gains obtained. Further, it would directly contradict the benefit cost rationale for trading in the first place. However, it is entirely possible that this rationale could prevail in the setting of offset market rules.

Below, the rationale for what discount rate to use in forest carbon projects is discussed. It is assumed that companies only get credit for the carbon in the year new carbon is created. One needs to compare the present value of the benefits derived from sequestering carbon over time to the present value of the costs. Consider the following example. Suppose a company considers investing in a project that has a stream of costs over time t, C_t, a stream of annual carbon sequestration (or losses), S_t, and a stream of the benefits of sequestering a ton of carbon in each year, P^c_t. This value is the price of carbon that would evolve in a carbon market, thus it represents the marginal costs of abating carbon in the next best alternative for the company, i.e., its opportunity cost for sequestering carbon. With a discount rate equal to r, a company would choose to invest in projects when the following condition holds (where r is the discount rate):

$$\text{(1a)} \qquad \int_1^X C_t e^{-rt} dt < \int_1^X P_t^c S_t e^{-rt} dt$$

Assuming that the price of carbon rises at a rate of "*g*" over time, this equation becomes (where P^c_0 is initial the benefit):

$$\text{(1b)} \qquad \int_1^X C_t e^{-rt} dt < \int_1^X P_0^c e^{gt} S_t e^{-rt} dt$$

which simplifies into

$$\text{(1c)} \qquad \int_1^X C_t e^{-rt} dt < \int_1^X P_0^c S_t e^{(g-r)t} dt$$

Note that for this analysis, no salvage value is assumed, thus the landowner retains the rights to the carbon. Further, the company that purchased the sequestration over the period of time in question must continue to hold sequestered tons beyond the project period, X, equal to the undiscounted stream of S_t. Companies may choose to renegotiate their contracts with existing landowners, purchase new contracts, or abate larger quantities on their own, depending on the relative costs of other alternatives.

From the perspective of a company considering investing in carbon sequestration in forests, it is important to include discounting in the analysis. Further, companies need to carefully consider both the choice of discount rates for carbon flows, and the time length of the project. Considering first, discount rates for carbon flows, the correct choice of discount rate will depend on assumptions about the future growth of the opportunity cost of carbon sequestration (P^c). If one assumes that carbon prices remain constant over time, then carbon flows should be discounted at financial rates of discounting (i.e., 6% in this case). To see this, solve (1c) for the cost per ton for a given project:

$$\text{(2)} \qquad \frac{\int_1^X C_t e^{-rt} dt}{\int_1^X S_t e^{(g-r)t} dt} < P_0^c$$

As can be seen in equation (2), if *g* is 0, carbon flows can be discounted at financial discount rates and the costs per ton can be compared to the current opportunity costs of carbon sequestration.

In today's policy context, however, the rate of growth of the value of carbon sequestration, *g* in (2) above, is likely to be positive. Nordhaus and Boyer (2000) suggest that with efficient policies, it would be 2-3%. With the Kyoto Protocol or other controls, carbon prices could rise much more quickly, potentially as much as 5 – 6% per year. For this analysis, we will consider two different assumptions about the rate of growth of carbon prices. One assumption is that carbon prices rise at 3% per year, and another is that they rise at 6% per year. Under the lower scenario, carbon flows are discounted at 3%, while under the higher scenario they are not discounted.

1.2. Increasing Forest Rotation Age

In this section, the costs of holding timber for additional years before harvesting in order to increase carbon on the site is estimated. Because many species are still growing at the time they are harvested, there exists potential to increase rotation ages to enhance carbon sequestration. Increasing rotation ages, however, has financial implications for landowners, by holding off the time of harvest and delaying the next rotation. For this study, costs in $ per ton of carbon are estimated for individual species for different land qualities, for different timber prices, and for different harvesting regimes. The costs are then aggregated across public and private lands by accounting for the proportions of different species and site classes in different counties.

Storing carbon by increasing rotation ages is likely to be feasible only on industrial forestlands that are managed in even-age rotation. Forests on industrial lands are more likely to have this history of even-aged management, so the potential to verify future intentions to set a baseline harvest condition will be possible. Some non-industrial private forestland owners who have a history of managing forests on an even aged basis may also provide sequestration by holding trees longer if they also have historical evidence about the harvesting practices on their land. In addition, many California private forests have professionally developed timber management plans as a result of state regulations, which may help verify baseline conditions.

Table 1-1. Timberland area, proportion of timberland type that is private, and proportions in different age classes for private and public lands.

Forest type	Total Area	Private Proportion	Private Proportion		Public Proportion	
	1,000 hectares	%	<60 yrs %	>60 yrs %	<60 yrs %	>60 yrs %
Douglas fir	310	62	59	41	14	86
Ponderosa Pine	1,961	69	44	56	41	59
W. White Pine	16	6	0	100	41	59
Fir-Spruce	548	19	40	60	21	79
Hemlock-Sitka	20	15	100	0	2	98
Lodgepole	179	13	40	60	13	87
Redwood	295	89	77	23	73	27
Hardwood	1,686	60	52	48	14	86
Unclassified/Other	2,180	4	--	--	--	--
Total	7,196	42	50	50	30	70

Source: USDA FIA

Of the major timber species, 62% of Douglas Fir, 69% of ponderosa pine, 13% of lodgepole, and 89% of redwood, are in private hands (**Table 1-1**). A relatively large proportion of hardwoods are also in private hands. In addition, 50% of private land is less than 60 years of age, and thus could potentially be contracted to be held for carbon sequestration. Only 30% of public land is less than 60 years, suggesting less potential.

To estimate the potential for increasing carbon by holding timber, yield functions for growing stock volume are developed for timber species in the region. Yield functions are generated for specific site qualities for each of the species listed in **Table 1-1**. All of the yield functions have the following functional form:

(3) Yield (m^3/hectare) = exp(a – b/age), for age <120 years

Yield (m^3/hectare) = exp(a – b/120), for age >120 years

In equation (3), a and b are parameters, and age is the age of the stand. The parameters for different timber types and site productivity classes are shown in **Table 1-2**. The timber types used in this analysis are drawn from the classification system used by the USDA Forest Service for its decadal Resource Protection Act assessment of United States forest resources. Carbon biomass is estimated with the following functional form adopted from Smith et al. (2003):

(4) Carbon (tons/hectare) = 0.5*(E*(F+(1-EXP(-Yield/G))))

Parameters for equation (4) for the different species are shown in **Table 1-3**, and are obtained from Smith et al. (2003).

Table 1-2. Estimated yield function parameters. Maximum yield using equation (3) is calculated for 120 year old stands. Maximum yield from FIA data is calculated as the maximum yield observed in the data.

Forest type	Parameter a	Parameter b	Maximum Yield from Eq. (3)	Maximum Yield from FIA data
			m^3/ha	
Douglas fir High	7.2	60.0	772.8	757.6
Douglas fir Med	6.8	60.0	518.0	586.2
Douglas fir Low	6.3	65.0	316.8	368.9
Pond. Pine High	6.8	70.0	501.0	424.4
Pond. Pine Med	6.2	70.0	275.0	345.5
Pond. Pine Low	6.0	90.0	190.6	156.5
Fir/Spruce High	6.9	80.0	509.5	528.0
Fir/Spruce Med	6.0	90.0	190.6	227.5
Lodgepole Avg.	6.0	70.0	225.1	257.0
Redwood High	7.3	80.0	760.0	919.7
Redwood Med	6.8	50.0	591.9	596.5
Hardwood High	6.0	30.0	314.2	390.9
Hardwood Med	6.1	60.0	270.4	267.8
Hardwood Low	5.4	60.0	134.3	150.1

Table 1-3. Carbon biomass parameters

Forest type	Parameters E	F	G	GSV at 70 years	Carbon at 70 years
				m^3/ha	t/ha
Douglas fir High	1719.4	0.0164	2155.5	540.7	204.8
Pond. Pine High	1127	0.0368	1536.5	330.3	129.7
Fir/Spruce High	741.8	0.0107	776.3	316.4	128.1
Lodgepole Avg.	1127	0.0368	1536.5	148.4	72.6
Redwood High	3738.2	0.0122	6752.8	472.1	149.0
Hardwood High	1244.6	0	1142.2	262.8	127.9

Source: Smith et al., 2003). (GSV = growing stock volume.)

To estimate the costs of storing carbon, one must focus on the lost economic opportunities associated with holding timber longer than the optimal rotation age. There are various benefits and costs associated with holding timber for longer periods. The basic Faustmann formula can be used to show many of these benefits and costs. The Faustmann formula represents the value of bare land in different types of timber:

(5) Stand Value = W(a) = $$\frac{P(a)V(a)e^{-ra} - C}{(1-e^{-ra})}$$

In equation (5), P(a) is the stumpage value of timber at age a, V(a) is the yield of merchantable timber at a, r is the discount rate, and C is the cost of establishing stands. Equation (5) shows the present value of harvesting stands [$P(a)V(a)e^{-ra}$] at age a minus the costs, C, invested at time 0.

The numerator in equation (5) is the value of a single rotation when land is planted to forests initially. The denominator in (5) accounts for the present value of rotating this stand by cutting at age a and replanting infinitely. The optimal age for harvesting trees is then found by taking the derivative of (5) with respect to timber age, a:

(6) $\dot{P}V + P\dot{V} = rP(a)V(a) + rW(a)$,

where $\dot{P}$ and $\dot{V}$ are the time derivatives of P(a) and V(a), i.e., dP(a)/da and dV(a)/da. Equation (6) shows that stands will be harvested at the age that equates the marginal benefits and marginal costs of waiting an additional year to harvest the trees. The marginal benefits include the benefits of obtaining price and yield growth. The marginal costs are opportunity costs of holding the timber stock and holding timberland. At the harvest time, marginal costs and marginal benefits of waiting are equal. Beyond the optimal harvest time, the marginal costs of waiting rise above the marginal benefits of waiting. From equation (6), the net marginal cost of waiting an additional year to harvest trees can be shown as:

(7) Net marginal cost of waiting a year = $rPV(a) + rW(a) - \dot{P}V - P\dot{V}$

Equations (6) and (7) suggest that there are two benefits of waiting to harvest timber stands, price growth and volume growth. Of course, if prices are declining, the price term becomes a cost. There are also two costs associated with holding mature stands, the interest costs associated with not harvesting the stand today, and the annual costs associated with holding timberland. The last term, the annual costs of holding timberland captures the effects that holding trees for a longer period of time on future, potentially longer, rotations.

For the analysis conducted here, it is assumed that contracts will be made with landowners to hold timberland that is nearing its optimal financial rotation age for some additional period of time. In the study, rotation ages are calculated independently for each species in each region of California. Optimal rotation ages depend on species growth rates, species-specific prices, costs, etc. It is also assumed that landowners are contracted to hold mature stands for discrete additional time periods (i.e., 5, 10, or 15 years longer than the optimal rotation age). Costs are then derived for these different holding periods.

The contracts analyzed for landowners are for 20 year and permanent contracts. For a 20-year contract, one might consider engaging with a landowner to hold trees for 5, 10, or 15 years longer than they would otherwise. Given the longer rotations in this region, contracts that are longer than 20 years, but less than permanent, make little sense.

Using equation (7), the costs of holding timber for a time period of X years longer are given as:

(8) Costs for a contract to hold trees an additional X years before harvesting =

$$\sum_{n=A}^{A+X} r[P(n)V(n)[1+r]^{-X} +$$
$$\{W(a) - W(A+X)[1+r]^{-X}\}$$
$$-\sum_{n=A}^{A+X} \{P(n)V(n) - P(n-1)V(n-1)\}[1+r]^{-X}$$

In equation (8), "A" is used to represent the original rotation period. The equation assumes that all future rotations are harvested at the older, (A+X), time period. In the empirical analysis below, these equations are adjusted to conform to the specific length of the contract with the landowners (i.e., 20 years or permanent).

The first term in the equation (8) is the present value of the annual interest cost associated with holding timber stock. At the optimal time of harvest, landowners who do not harvest mature stock lose out on the opportunity to take the value P(A)*V(A) and invest it either in the bank or another asset, both of which earn a market rate of return of r. These interest costs grow over time as the stand continues to grow. The second term accounts for delaying the next rotation by X years. It is the difference between the value of establishing a new stand today, W(a), and the present value of establishing a new stand X years from now, W(A+X). Note that one assumption in this analysis is that the new stand will be harvested in longer rotations as well, such as would be the case with 40- or 80-year contracts. An alternative assumption would be that future rotations return to the original rotation ages, such as with 20-year contracts. The final term is the benefit of waiting to harvest. It is the present value of the growth in stand value over time. The marginal cost (MC) of waiting X years to harvest a stand is thus:

(9) MC = (Costs of a contract of period X) /

(Carbon gains for a contract of period X).

A critical issue in estimating the cost revolves around estimating the increase in carbon on the site, i.e., the denominator in equation (9). To show how the change in carbon is calculated, an example using high site[1] quality Douglas fir, one of the most common species used commercially in California, was developed. High site quality Douglas fir in California timber region 7 (northern Sierras) is estimated to be harvested at an optimal rotation period of 48 years of age. It is important to recognize that economically optimal timber harvest ages are typically lower than timber harvesting ages mandated by law. The reason for this is that opportunity costs of holding mature timber grow rapidly as timber growth slows. The first important piece of information needed to estimate potential carbon gains in the yield function is shown in **Figure 1-1**.

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1 *High site* refers to a site with good growing conditions.

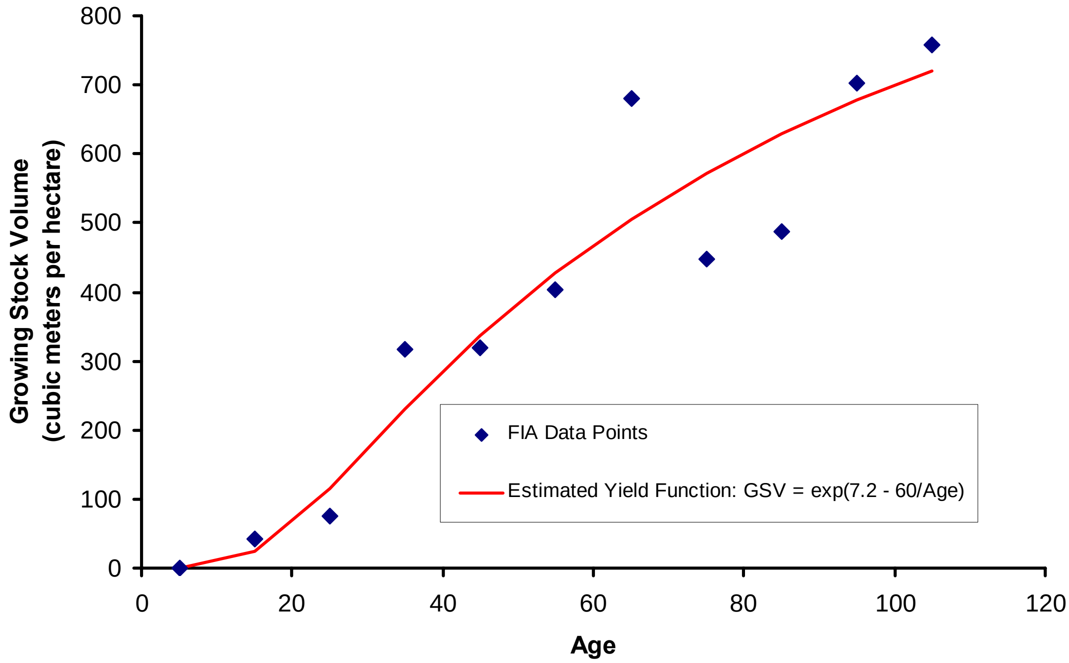

Figure 1-1. Growing stock volume yield function for high site Douglas Fir in California.

From growing stock, carbon biomass accumulation is estimated using parameters from Smith et al (2003) to convert growing stock to biomass. Several assumptions are used to estimate storage in products. First, it is assumed that 43% of the biomass enters into wood products, the rest being emitted immediately (Birdsey 1996). For Douglas fir, 85% of the biomass in wood products is assumed to enter solid-wood products, and 15% enters pulpwood products (the proportion increases with age up to 90%). Solid-wood products are assumed to decay at 2% per year, and pulpwood products are assumed to decay at 5% annually.

Figure 1-2 shows total carbon associated with one hectare of high site Douglas Fir stands that are 48 years old at period 0. Baseline carbon stocks (blue line) start at approximately 98 tons carbon, which is the carbon stored in products at harvest. Carbon storage declines for the first 10 or so years in the baseline as carbon is emitted from shorter-lived wood products, and carbon regrowth on the land is not fast enough to offset these emissions. Carbon storage in the longer rotations (the red line) starts at 146 tons C per hectare, and rises to approximately 160 tons per hectare at age 53. When the stand is harvested, carbon immediately declines to 70 tons per hectare, and there are net emissions for several years from products. In addition to showing the annual stocks of carbon in the two scenarios, average carbon for the two scenarios is shown. There are approximately 8 additional tons C per hectare on stands held five more years before harvesting.

To calculate the carbon consequences for the atmosphere of these two alternatives, it is necessary to estimate the net annual flux of carbon under each scenario, and then take the difference between the two flux estimates. This difference is shown in **Figure 1-3** (net annual flux of carbon for the longer rotation—net annual flux of carbon for the baseline rotation). As can be seen in the figure, there is an initial negative carbon flow, which simply indicates that more carbon would have been stored in products initially in the baseline with a harvest at year 63 than grows that year in a stand being held. Additional carbon accumulates on the ground for the longer rotation scenario, and at year 5 when harvests are assumed to occur for that rotation, there is a large positive value representing carbon storage in harvested products. The present value of the path in **Figure 1-3** represents the net present value of the gain to the atmosphere from converting to longer rotations.

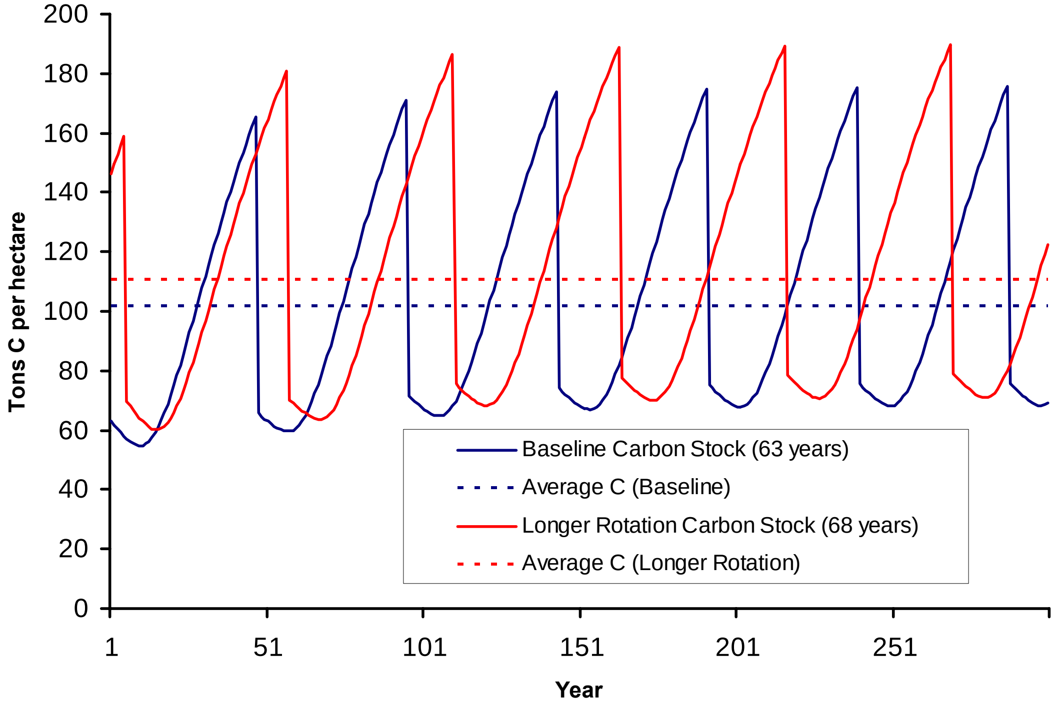

Figure 1-2. Tons carbon per hectare stored in aboveground biomass and products, assuming stands are initially 63 years old.

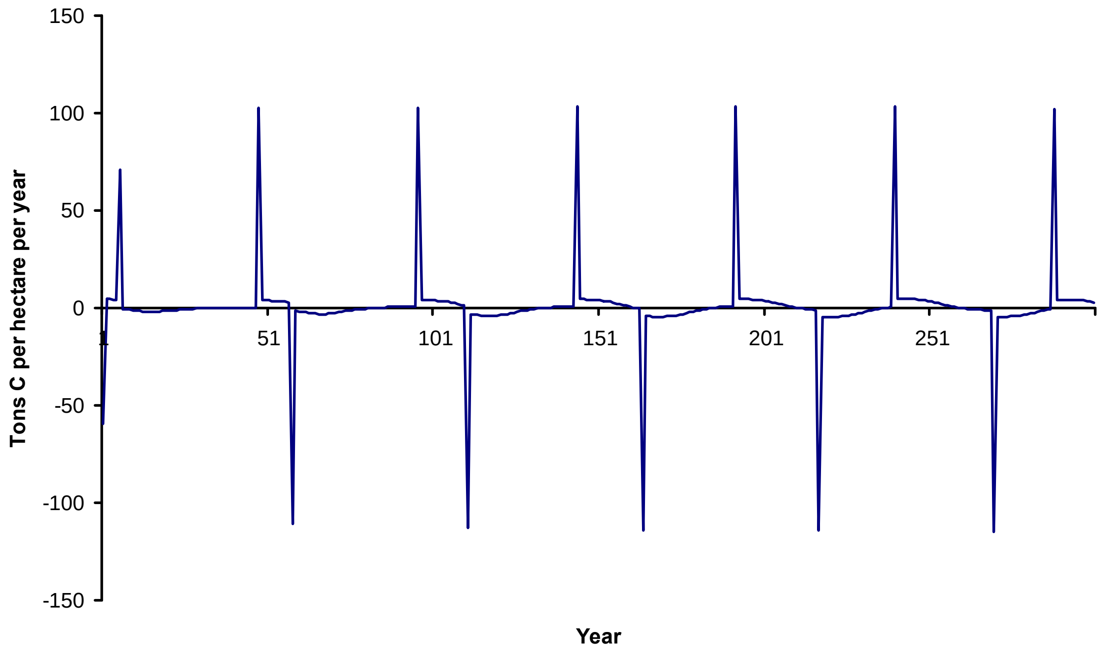

Figure 1-3. Difference in net annual flux for the longer rotation scenario versus the baseline scenario (long rotation net annual flux of carbon – baseline rotation net annual flux of carbon).

There are essentially three components to the carbon gain (or loss if the stand is not growing biomass fast enough to offset the effects of carbon discounting). The first component is the change in storage in market products due to an increase in the size of the stand that is ultimately harvested. Future stands will be harvested at an older age, with more merchantable volume, and hence more carbon will be stored in the market products. The value of this gain from the perspective of today, where MS(A+X) is "market storage" in the lengthened rotation and MS(A) is the market storage in the original rotation, is given as:

(10) Market Carbon Gain = MCG(A+X) = $MS(A+X)[1+r]^{-X} - MS(A)$

Equation (10) captures only the difference in market storage for the first harvest. Storage in future harvests is captured below in equation (11). Correctly accounting for the market storage change in (10) will also include the emissions from wood product decay over time, although those decays are not show in the equation.

The second component is the change in the present value of the carbon gains associated with establishing a new stand on the site and holding it in the baseline rotation or holding it in a longer rotation. The value of this gain is given as:

(11) Stand Carbon Gain = SCG(A+X) = $SC(A+X)[1+r]^{-X} - SC(A)$

where

$$SC(A+X) = \sum_{0}^{M} \rho^{t} \left\{ CG(t) - HE(t) - PD(t) \right\}.$$

In Equation 11, SC(A) is the site carbon for a new stand established and held for the original rotation, and SC(A+X) is the site carbon for a new stand established and held for the lengthened rotation. CG(t) is the carbon gain associated with forest growth in year t, HE(t) is the emission that occurs at the time of harvest (which will be 0 in all years t where harvests do not occur), PD(t) is the decay from products, and M is the time period for accounting. Each of these values is obtained by estimating growing stock volume with regional yield functions for different site classes, and using the assumptions discussed above to convert growing stock to carbon and harvested products to storage and decay. It is assumed that future stands are also harvested at the older rotation age (A+X) when calculating (11).

The final component is gain in forest growth over the period from age A to (A + X). This is:

(12) Net Carbon Growth = $NG(A+X) = \sum_{n=A}^{A+X} \left\{ V(n) * BEF(n) - V(n-1) * BEF(n-1) \right\} \left[1+r \right]^{-n}$

For equation 12, BEF(n) is the biomass expansion factor, measured as Mg C/m^3. This is derived by combining equations 3 and 4 above. With equations 10, 11, and 12, carbon gains for the contract period can be estimated as:

(13) Carbon Gains for a contract of period X =

$$MCG(A+X) + SCG(A+X) + NG(A+X)$$

To see the implications of the flows in equations 10–12, the values for the Douglas fir high site example discussed above are shown in **Table 1-4**. The first row (r1) of the table presents the tons of carbon stored in aboveground biomass at age 48 or at age 53. The second row (r2) shows the tons stored in wood products at both ages. More carbon is stored in products harvested from an older stand (69.7 versus 63.0 tons per hectare), but when these values are discounted (third column) to the initial period when the decision to hold the trees or not is made, the present value (PV) storage in the younger rotation is larger (63.0 versus 60.1). The reason for this is that the carbon discount rate is 3% and the trees are growing more slowly than 3% per year. The third row (r3), then, shows the present value of the carbon stored in products for the first harvest only. This calculation accounts for the present value of decay in products over time.

The fourth row (r4) shows the present value of stored carbon in a newly planted stand harvested either at 48 or 53-year rotations. In 48-year rotations, the present value of carbon is 46.4 tons per hectare, while in 53 year rotations it is 50.5 tons per hectare. However, one must wait five years in the older rotation to get the carbon associated with that option, so that value must be discounted. When discounted to year 0, the carbon gain associated with a newly planted Douglas Fir stand harvested in 53-year rotations is 43.6 tons per hectare.

Table 1-4. Carbon values for high site Douglas Fir

	Rotation Age 48	Rotation Age 53		Difference
	Value in PV Terms	Value 5 years from now	Value in PV terms	Between Rotations (c3 – c1)
	c1	c2	c3	c4
(r1) Mg/ha	146.49	162.10		
(r2) Mg stored in products (first harvest only)	62.99	69.70	60.13	
(r3) PV carbon stored in products	35.67	39.47	34.05	-1.62
(r4) PV carbon in future rotations	46.44	50.52	43.58	-2.87
(r5) Carbon in additional biomass growth		15.95	14.62	14.62
(r6) Sum (r3 + r4 + r5)	82.11	105.93	92.25	10.13

The fifth row (r5) is the additional growth associated with holding the stand an additional 5 years. During this time period, an additional 16.0 tons is stored on the site. When discounted this is reduced to 14.6 tons of additional "present value" carbon accumulated on the site. The sixth row (r6) presents the sum of carbon accumulation under the two alternatives (harvest today or wait 5 years to harvest). The first and the third columns should be compared for correct present value comparisons. The results of these differences are shown in column 4. Note that column four also represents the sum of the present value of flows shown in **Figure 1-3** above.

One issue to consider with these marginal cost curves is that alternative crediting methods could alter the results. In particular, as noted in Section 1-3 below, different methods of crediting carbon could have important implications for measuring the costs of different actions to sequester carbon. The empirical estimates in this section focus on the methods used above, while alternative methods for carbon accounting are developed and used in **Appendix A**.

1.2.1. Empirical estimates of marginal costs

For this analysis, marginal costs are estimated with the methods above for all of the species and site classes listed in **Table 1-2**. Regional stumpage prices are available for 11 regions in California (California State Board of Equalization, Harvest Values Schedule, 2002), allowing for variation in estimating the cost of carbon sequestration across the state. To give readers a sense for stumpage prices in the state, prices for the period January 1, 2003 – June 30, 2003 are shown in **Table 1-5** for these regions. Stumpage prices in $ per thousand board feet are converted to $\$/m^3$ using the following conversion factors:

$$\$/m^3 = \$/MBF*(208cf/MBF)*(0.0283\ m^3/cf)$$

where MBF is thousand board feet, and cf is cubic feet. The conversion factor of 208 cf/MBF was obtained by comparing sawtimber volumes in MBF to growing stock volumes in cubic feet from the USDA Forest Service FIA database (FIA). The prices in **Table 1-5** are for the sawtimber proportion of the solidwood on the site. On average for California, 88% of the growing stock volume in stands above 50 years old is sawtimber.

Table 1-5. Timber prices for the period January 1, 2003–June 30, 2003, obtained from the California State Board of Equalization Harvest Schedule.

Region	Ponderosa Pine	Hem/Fir	Doug. Fir	Redwood	Western Hwds	Pulp and Miscell.
	$ per m^3 growing stock volume					
R1	45.28	15.28	57.16	105.83	33.96	12.55
R2N	42.45	13.58	41.31	105.83	33.96	12.55
R2S	37.07	11.88	39.05	101.30	33.96	12.55
R3	65.08	25.47	58.29	99.46	33.96	12.55
R4	61.69	30.56	61.69	99.46	33.96	12.55
R5	63.39	28.86	59.99	84.89	33.96	12.55
R6	62.82	39.05	67.35	99.46	33.96	12.55
R7	68.48	32.26	65.08	84.89	33.96	12.55
R8	66.22	28.86	57.73	99.46	33.96	12.55
R9N	63.95	33.96	35.65	84.89	33.96	12.55
R9S	30.56	15.28	15.28	99.46	33.96	12.55

There are additional costs of managing forests in California that must be included in the calculations. The first is timber taxation. California has two applicable taxes: a severance tax on timber harvested and many local jurisdictions have taxes on private land, although these land value taxes are at substantially reduced rates due to favorable valuations. The severance tax in California currently is 2.9% (California State Board of Equalization; www.boe.ca.gov), and the current average statewide property tax rate is 1.07% (or $1.07 per $100). In addition to taxes, many landowners must develop timber management plans in order to harvest trees. These plans can be quite expensive to develop, particularly initially. Using estimates from California Forest Improvement Program (2003), these costs range from $5.76 per hectare to $11.75 per hectare.

Based on California Forest Improvement Program (2003), regeneration costs for California forests are estimated to range from $395 per hectare to over $1,500 per hectare, depending on site conditions and the amount of site preparation necessary. For this analysis, the lower value of $395 per hectare is used because the values will ultimately be aggregated and presented spatially. Many landowners are likely to choose lower levels of regeneration when available and hence the $395/ha value is deemed most appropriate for aggregation across sites. When considering how these costs relate to potential costs at a particular site, note that anything that increases initial establishment costs will also raise the costs of carbon sequestration.

Estimates of the costs of holding carbon in forests by aging timber are developed for each species and site class in each region listed in **Table 1-6**. Values for specific counties in each region are then developed by considering the proportion of age classes in each county and weighting the costs across the site qualities.

One issue that arises when estimating the value of holding timber revolves around the rotation age. Optimal economic rotation ages calculated with (5) above typically are lower than maximum sustained yield, and they are lower than harvest ages implied by law for California (California Forest Practices Act, Article 3). Prices, calculated optimal rotation ages, timber yields and site values for species in California timber region 7 are shown in **Table 1-6**. Timber region 7 is the northern Sierra Nevada mountain region in California. These same values are shown in **Table 1-7** for rotation ages consistent with the law.

When comparing the values in **Tables 1-6 and 1-7**, one can see that the site values decline substantially under California laws that regulate harvesting ages. In general, anything that extends the rotation age beyond the optimal rotation age will decrease site value (and anything that decreases the rotation from the optimal age will have the same effect). To account for different rotation ages that might be used in practice, both the optimal rotation ages and the rotation ages required by law are used for the study, and results are provided for both.

Potential carbon sequestered and the marginal costs for permanent rotation changes are shown in **Tables 1-8 and 1-9** for California timber region 7 (the same region as discussed in **Tables 1-6 and 1-7** above). As one can see from the table, the costs of carbon sequestration are fairly high. With the relatively high rotation ages suggested for species in the west, growth rates are slow near the optimal rotation ages, and thus there is not substantial additional accumulation of carbon for longer rotation periods. Fir/Spruce forests appear to have the lowest cost per ton. All species have greater carbon accumulation on higher site classes, and comparably lower costs.

In all cases, costs are substantially higher under the scenario that assumes all species are harvested at the legal rotation age. The reason for this is that carbon growth slows substantially moving to these older rotation ages. Land values in the region are relatively low, as shown in **Tables 1-6 and 1-7**, and consequently, the costs of increasing rotation ages are not all that high. However, carbon gains also are not large, particularly when present value analysis is used to discount the carbon gains.

The results for 20-year contracts with discounted carbon are presented in **Tables 1-10 and 1-11**. Carbon gains are generally smaller, or negative, for 20-year contracts, and consequently costs are higher. However, one can note that the carbon gains rise rapidly for longer holding periods. For shorter contract periods, there are substantial benefits associated with holding timber on the stump for longer periods in order to avoid the lower carbon accumulation rates associated with younger stands and the carbon emissions associated with forest products. Note, though, that even the lowest carbon sequestration costs for 20-year contracts tend to suggest higher costs than permanent contracts for longer rotations.

Results for 20-year contracts assuming that carbon is not discounted are shown in **Tables 1-12 and 1-13**. Carbon gains are largest for longer holding periods, as carbon accumulation rates for stands near their optimal rotation age are faster than accumulation rates for younger stands in the first 20 years and emissions from forest products. As a consequence, carbon sequestration costs decline for longer holding periods.

One issue to note with these estimates of the marginal costs is that they assume a particular set of property rights that essentially provide credit for long-term storage in wood products, but that do not provide credit for storage of carbon in existing stands. From the perspective of the atmosphere, holding timber stocks for additional time should be just as valuable as placing it in long term wood product storage. Thus an alternative method for crediting carbon storage is developed to credit carbon sequestration in forests, and these estimates are provided under this alternative method. This is discussed further in **Appendix A**.

Table 1-6. Prices, optimal rotation ages, timber yield and site values.

	Sawtimber Price	Rotation Age	Yield	Site Value
	$/m³	yr	m³/ha	$/ha
HWD Hi	$32.97	48	216.84	$9.88
HWD Med	$32.97	54	145.66	-$28.03
HWD Low	$32.97	54	73.61	-$53.49
DF Hi	$63.20	48	367.66	$637.43
DF Med	$63.20	56	289.91	$73.95
DF Low	$63.20	64	198.46	-$263.11
PP Hi	$66.49	50	223.74	$114.87
PP Med	$66.49	58	146.27	-$243.29
PP Low	$66.49	68	106.99	-$389.25
FS Hi	$31.32	50	200.05	-$229.63
FS Med	$31.32	66	102.36	-$440.92
LP Avg.	$66.49	58	120.42	-$295.85
RW Hi	$82.43	52	318.91	$447.56
RW Med	$82.43	55	361.31	$427.14

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-7. Prices, timber yield and site value under regulated rotations.

	Sawtimber Price	Rotation Age	Yield	Site Value
	$/m³		m³/ha	$/ha
HWD Hi	$32.97	70	262.81	-$68.57
HWD Med	$32.97	70	189.21	-$65.11
HWD Low	$32.97	70	93.96	-$71.74
DF Hi	$63.20	50	383.75	$563.29
DF Med	$63.20	60	314.19	-$28.81
DF Low	$63.20	80	241.65	-$382.89
PP Hi	$66.49	50	221.41	$123.33
PP Med	$66.49	60	153.44	-$267.54
PP Low	$66.49	80	130.97	-$430.85
FS Hi	$31.32	60	261.56	-$309.99
FS Med	$31.32	80	130.97	-$463.34
LP Avg.	$66.49	70	148.41	-$382.13
RW Hi	$82.43	50	298.87	$519.18
RW Med	$82.43	80	480.58	-$273.42

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-8 (*Permanent Contract – Discounted Carbon*). Net carbon sequestered and $ per ton for increasing rotation ages X years above economically optimal rotation ages (the rotation ages for this analysis are shown in Table 1-6) in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	2.82	3.36	2.13	$37	$97	$319
HWD Med	6.03	9.39	10.66	$14	$36	$72
HWD Low	3.12	4.99	5.77	$17	$43	$75
DF Hi	10.13	16.02	18.93	$367	$438	$521
DF Med	3.66	5.13	5.13	$855	$1,126	$1,555
DF Low	0.86	0.71	-0.11	$2,573	$5,729	--
PP Hi	6.22	9.92	11.82	$353	$423	$503
PP Med	1.50	1.92	1.63	$1,038	$1,513	$2,491
PP Low	0.33	0.12	-0.44	$3,565	$17,555	--
FS Hi	9.12	15.21	19.00	$89	$106	$124
FS Med	2.32	3.77	4.58	$228	$262	$301
LP Avg.	1.03	1.19	0.76	$1,241	$2,018	$4,393
RW Hi	8.75	14.64	18.34	$427	$491	$560
RW Med	1.25	0.82	-0.70	$4,333	$12,086	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-9 (*Permanent Contract – Discounted Carbon*): Net carbon sequestered and $ per ton for increasing rotation ages X years above the legally mandated rotation age in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	-6.14	-12.15	-17.87	--	--	--
HWD Med	0.43	-0.02	-1.04	$2,045	--	--
HWD Low	0.39	0.30	-0.11	$1,117	$2,603	--
DF Hi	8.77	13.61	15.71	$453	$547	$662
DF Med	2.09	2.37	1.45	$1,647	$2,674	$5,989
DF Low	-2.10	-4.53	-7.12	--	--	--
PP Hi	6.22	9.92	11.82	$347	$416	$496
PP Med	1.08	1.19	0.65	$1,549	$2,617	$6,625
PP Low	-0.96	-2.18	-3.54	--	--	--
FS Hi	5.10	7.96	9.22	$259	$312	$377
FS Med	0.63	0.72	0.45	$1,211	$1,919	$4,240
LP Avg.	-0.85	-2.14	-3.69	--	--	--
RW Hi	9.54	16.09	20.34	$350	$406	$462
RW Med	-5.54	-11.10	-16.48	--	--	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-10 (*20-yr Contract- Discounted Carbon*). Net carbon sequestered and $ per ton for increasing rotation ages X years above economically optimal rotation ages (the rotation ages for this analysis are shown in Table 1-6) in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	-9.00	-17.68	-21.95	--	--	--
HWD Med	1.45	3.53	5.95	$59	$97	$130
HWD Low	0.88	2.11	3.47	$62	$102	$125
DF Hi	1.31	4.25	8.71	$2,726	$1,602	$1,105
DF Med	-1.59	-1.57	-0.08	--	--	--
DF Low	-1.70	-2.35	-2.21	--	--	--
PP Hi	1.57	3.65	5.89	$1,345	$1,119	$988
PP Med	-1.15	-1.77	-1.95	--	--	--
PP Low	-0.99	-1.84	-2.56	--	--	--
FS Hi	5.79	11.58	16.52	$141	$140	$143
FS Med	1.82	3.57	4.99	$291	$277	$276
LP Avg.	-1.37	-2.27	-2.75	--	--	--
RW Hi	4.69	9.30	13.30	$770	$755	$757
RW Med	-5.15	-8.60	-9.42	--	--	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-11 (*20-yr Contract- Discounted Carbon*). Net carbon sequestered and $ per ton for increasing rotation ages X years above the legally mandated rotation age in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	-13.75	-26.06	-32.93	--	--	--
HWD Med	-2.00	-2.39	-1.54	--	--	--
HWD Low	-0.81	-0.86	-0.31	--	--	--
DF Hi	0.35	2.54	6.44	$9,636	$2,498	$1,389
DF Med	-2.69	-3.51	-2.68	--	--	--
DF Low	-3.80	-6.08	-7.20	--	--	--
PP Hi	1.57	3.65	5.89	$874	$729	$646
PP Med	-1.44	-2.28	-2.64	--	--	--
PP Low	-1.90	-3.49	-4.79	--	--	--
FS Hi	2.87	6.31	9.39	$234	$200	$188
FS Med	0.59	1.34	1.95	$663	$528	$493
LP Avg.	-2.69	-4.62	-5.90	--	--	--
RW Hi	5.23	10.29	14.68	$770	$770	$783
RW Med	-9.86	-16.86	-20.37	--	--	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce;
LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality;
Low = low site quality; Avg =average site quality.

Table 1-12 (*20-yr Contract- UnDiscounted Carbon*). Net carbon sequestered and $ per ton for increasing rotation ages X years above economically optimal rotation ages (the rotation ages for this analysis are shown in Table 1-6) in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	-9.38	-19.66	-23.02	--	--	--
HWD Med	2.29	7.20	13.99	$37	$47	$55
HWD Low	1.36	4.11	7.78	$40	$53	$56
DF Hi	3.03	11.49	25.00	$1,175	$592	$385
DF Med	0.10	4.02	11.59	$31,413	$1,407	$678
DF Low	-0.05	2.11	6.07	--	$1,919	$914
PP Hi	3.54	9.63	17.38	$596	$424	$335
PP Med	0.35	2.03	4.79	$4,497	$1,432	$846
PP Low	0.70	1.75	3.08	$1,660	$1,236	$973
FS Hi	8.23	19.31	31.16	$99	$84	$76
FS Med	3.53	7.84	12.28	$150	$126	$112
LP Avg.	-0.06	0.92	2.81	--	$2,611	$1,191
RW Hi	7.91	18.14	29.32	$457	$387	$344
RW Med	-4.13	-5.37	-1.77	--	--	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality;
Low = low site quality; Avg =average site quality.

Table 1-13 (*20-yr Contract- UnDiscounted Carbon*). Net carbon sequestered and $ per ton for increasing rotation ages X years above the legally mandated rotation age in California timber region 7.

	t C per hectare			$ per t C		
	5 years	10 years	15 years	5 years	10 years	15 years
HWD Hi	-13.84	-28.23	-35.11	--	--	--
HWD Med	-0.93	1.29	6.23	--	$1,230	$346
HWD Low	-0.19	1.19	3.91	--	$665	$274
DF Hi	2.18	9.86	22.69	$1,755	$734	$449
DF Med	-0.87	2.19	9.00	--	$2,887	$968
DF Low	-1.84	-1.27	1.26	--	--	$5,642
PP Hi	3.54	9.63	17.38	$586	$417	$330
PP Med	0.09	1.55	4.12	$17,663	$2,007	$1,052
PP Low	-0.03	0.34	1.06	--	$8,320	$3,683
FS Hi	5.71	14.41	24.09	$231	$172	$144
FS Med	2.55	5.94	9.52	$300	$234	$199
LP Avg.	-1.20	-1.24	-0.26	--	--	--
RW Hi	8.32	18.98	30.57	$387	$334	$301
RW Med	-8.31	-13.17	-12.72	--	--	--

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce;
LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality;
Low = low site quality; Avg =average site quality.

1.2.2. Potential Carbon Sequestration in Region

In this section, aggregate results for potential sequestration in the entire state are provided. The aggregation is accomplished by using USDA Forest Service FIA data to break stocks of forests in each region into forests below and above 60 years of age. Forests younger than 60 years of age are assumed to be available for contracts that would increase the rotation period for carbon sequestration purposes. Forests older than 60 years of age are assumed not to be available for this treatment. Note that for this analysis, all lands potentially treatable are assumed to be treated. There are two implications of this. First, cost estimates will be substantially higher than what is likely to occur in reality where only the lowest cost lands are selected into the program. Second, in some cases, longer holding periods result in less carbon sequestration, and sometimes "negative" sequestration. When sequestration is estimated to be negative, the option drops out of the aggregate calculation.

The results for the permanent contracts for private and public lands are shown in **Table 1-14**. There are similar land areas that could be treated in each ownership group, however the carbon potential on private lands is, not surprisingly, greater. The main reason for this is that private lands in general have higher site quality classes than public lands, and also more productive species types. Average costs per ton are also higher on private lands because opportunity costs tend to be higher for better quality land and more commercially useful species. While it appears that costs are lower for the 15 year holding case, note that in all cases, individual contracts will be more expensive. The aggregate results suggest lower costs for the 15-year contracts because some very costly options drop out of the aggregation due to "negative" sequestration, as discussed above.

Table 1-14 (*Permanent Contract – Discounted Carbon*). Aggregate estimated carbon potential with holding timber past economically optimal rotation periods.

	Waiting Period		
	5 yr.	10 yr.	15 yr.
Private Land Potential Hectares	319,632		
Million Tons	1.16	1.77	1.99
Million $	189.64	382.63	446.90
Average $ per ton C	$163.29	$216.17	$224.39
Average $ per hectare	$593.29	$1,197.10	$1,398.18
Average ton C per hectare	3.63	5.54	6.23
Public Land Potential Hectares	336,371		
Million Tons	0.60	0.94	1.12
Million $	94.04	176.30	204.64
Average $ per ton C	$156.90	$186.79	$182.29
Average $ per hectare	$279.57	$524.13	$608.36
Average ton C per hectare	1.78	2.81	3.34

The results for the two 20 year contracts are shown in **Tables 1-15 and 1-16**. Overall carbon sequestration potential is smaller for the 20 year discounted scenario, but costs are also lower. The reason costs are lower is that deviations in future rotations are not considered in the cost calculations. The undiscounted scenario in **Table 1-16** shows the overall carbon potential of the region for the next 20 years. With a 15-year increase in rotation ages, forests in the region could sequester up to 9.8 tons per hectare, for a total of 3.14 million tons. Of course, these are not permanent tons, and the permanent value of the sequestration would be much lower. They nevertheless represent substantial potential on the hectares available, although the potential is fairly costly ($264 per ton on private land).

Table 1-15 (*20-yr Contract- Discounted Carbon*). Aggregate estimated carbon potential with holding timber past economically optimal rotation periods.

	Waiting Period		
	5 yr.	10 yr.	15 yr.
Private Land Potential Hectares	319,632		
Million Tons	0.32	0.71	1.13
Million $	$59.20	$134.24	$216.68
Average $ per t C	$185.30	$188.83	$191.52
Average $ per hectare	$185.22	$419.99	$677.92
Average t C per hectare	1.00	2.22	3.54
Public Land Potential Hectares	336,371		
Million Tons	0.29	0.58	0.86
Million $	$59.57	$120.86	$179.55
Average $ per t C	$208.88	$207.30	$209.75
Average $ per hectare	$177.10	$359.31	$533.79
Average t C per hectare	0.85	1.73	2.54

Table 1-16 (*20-yr Contract- UnDiscounted Carbon*). Aggregate estimated carbon potential with holding timber past economically optimal rotation periods.

	Waiting Period		
	5 yr.	10 yr.	15 yr.
Private Land Potential Hectares	319,632		
Million Tons	0.58	1.68	3.14
Million $	136.02	586.63	828.47
Average $ per t C	$233.54	$348.50	$263.57
Average $ per hectare	$425.54	$1,835.33	$2,591.94
Average t C per hectare	1.82	5.27	9.83
Public Land Potential Hectares	336,371		
Million Tons	0.48	1.19	2.03
Million $	116.92	285.30	438.69
Average $ per t C	$245.92	$240.32	$216.54
Average $ per hectare	$347.59	$848.16	$1,304.18
Average t C per hectare	1.41	3.53	6.02

To capture this potential additional carbon, one would start with the lowest cost opportunities first and move towards higher cost opportunities if prices for carbon sequestration rise. A marginal cost curve is thus developed to present the alternatives (**Figures 1-4 through 1-6**). Three marginal cost curves are developed for the three alternatives considered, permanent contracts, and 20-year contracts with discounted and undiscounted carbon. The marginal cost curves are arbitrarily cut-off at carbon costing >$2000 per ton.

The spatial distribution at the country scale of resolution of the amount of additional carbon that could be sequestered by lengthening for 5 years and the costs with 20-year contracts are shown in **Figures 1-7 and 1-8**. The least expensive counties do not produce the highest quantities of carbon.

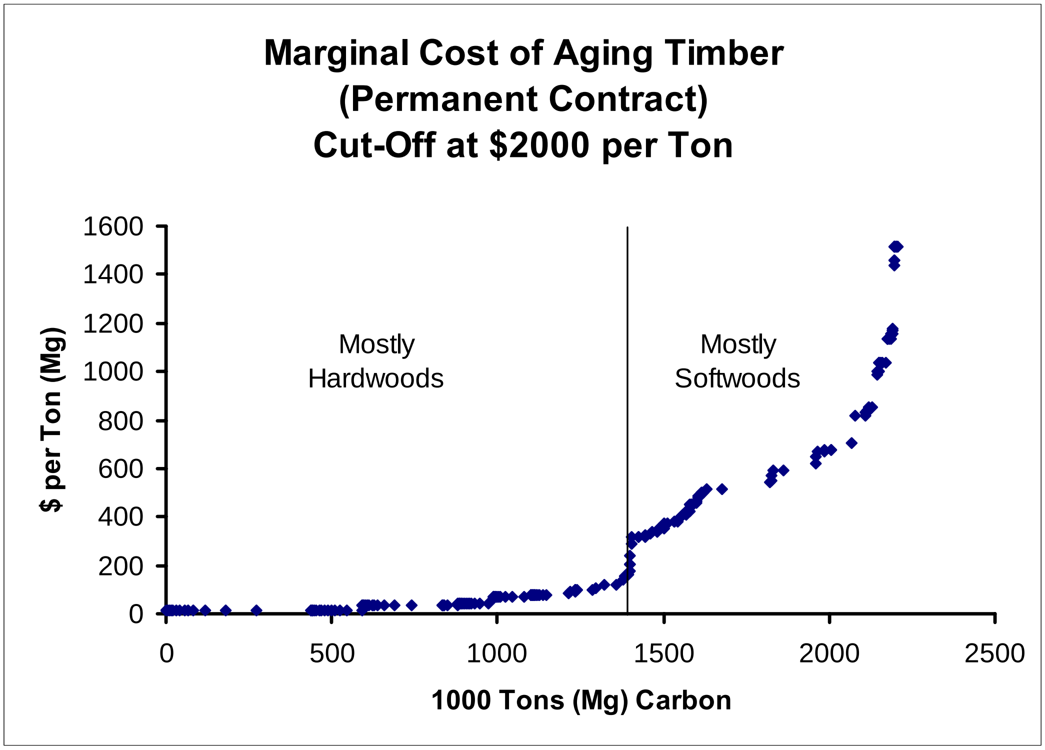

Figure 1-4. Marginal cost of aging timber with permanent contract on private land only (discounted carbon)

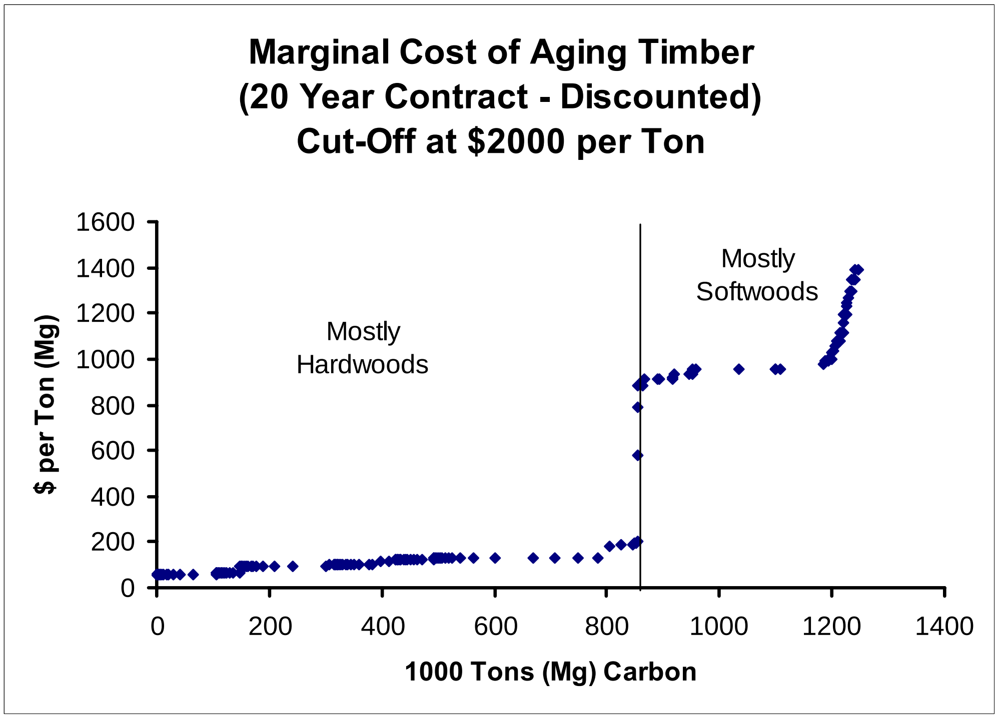

Figure 1-5. Marginal cost of aging timber with 20-year contracted on private land only (discounted carbon)

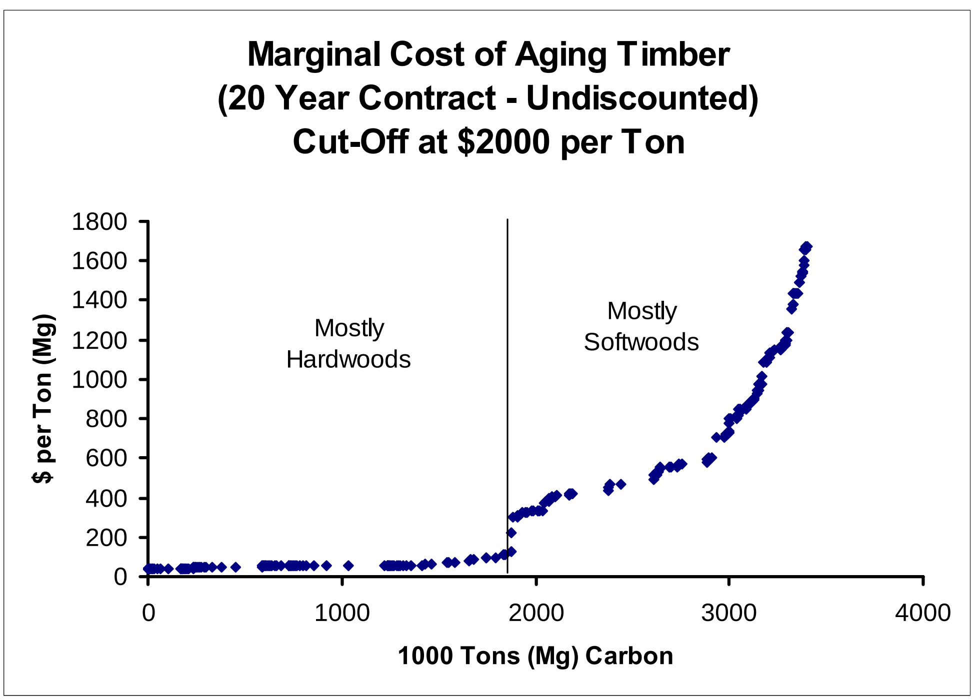

Figure 1-6. Marginal cost of aging timber with 20-year contract on private land only (undiscounted carbon)

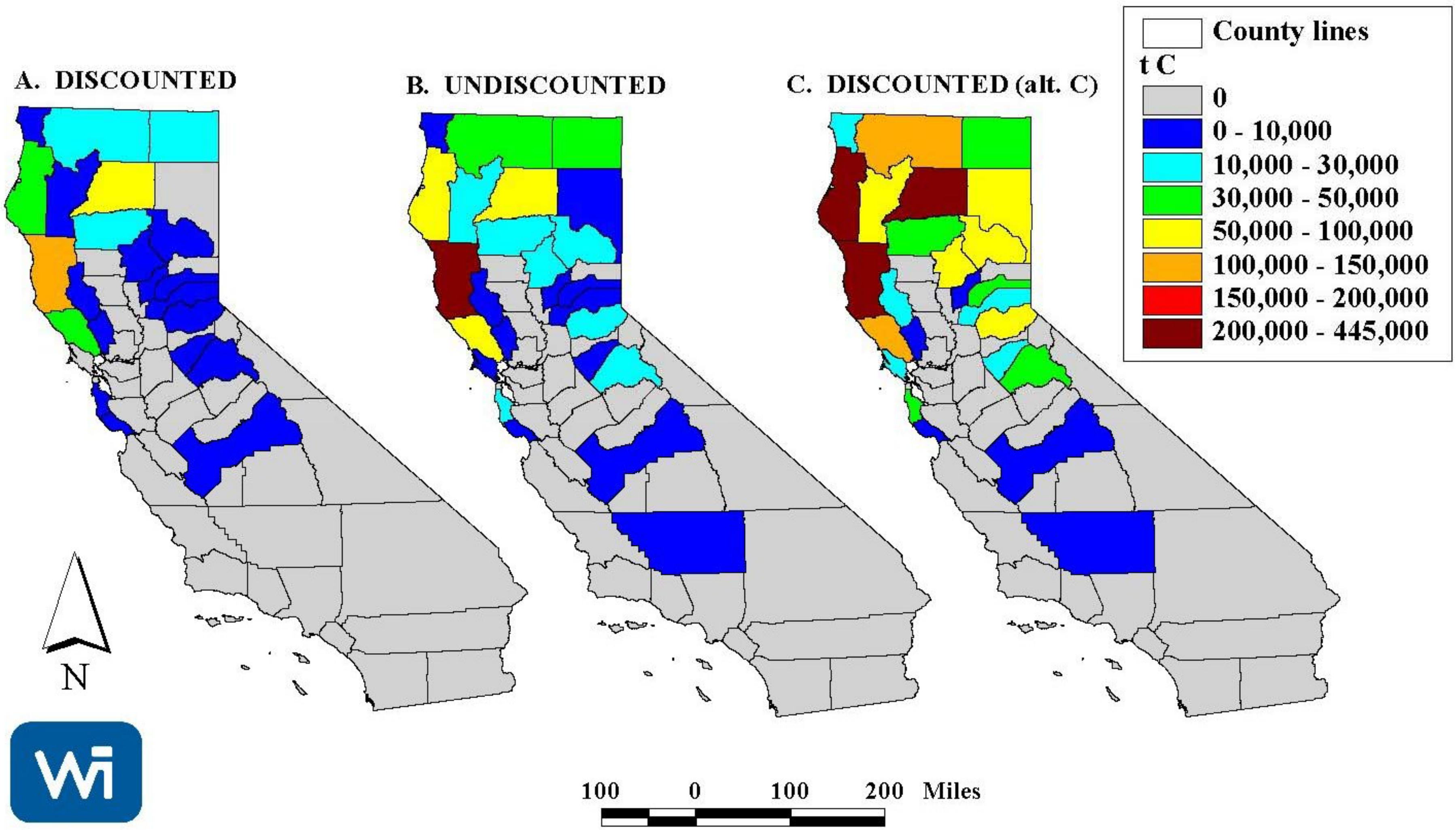

Figure 1-7. Distribution, at the county scale of resolution, of the potential amount of carbon with 20-year contracts that could be sequestered on all lands by lengthening the forest rotation time by 5 years for A. discounted carbon, B. undiscounted carbon, and C. discounted carbon (for A. and B. see Tables 1-15 and 1-16, and for C. see Appendix A, Table A3 for details).

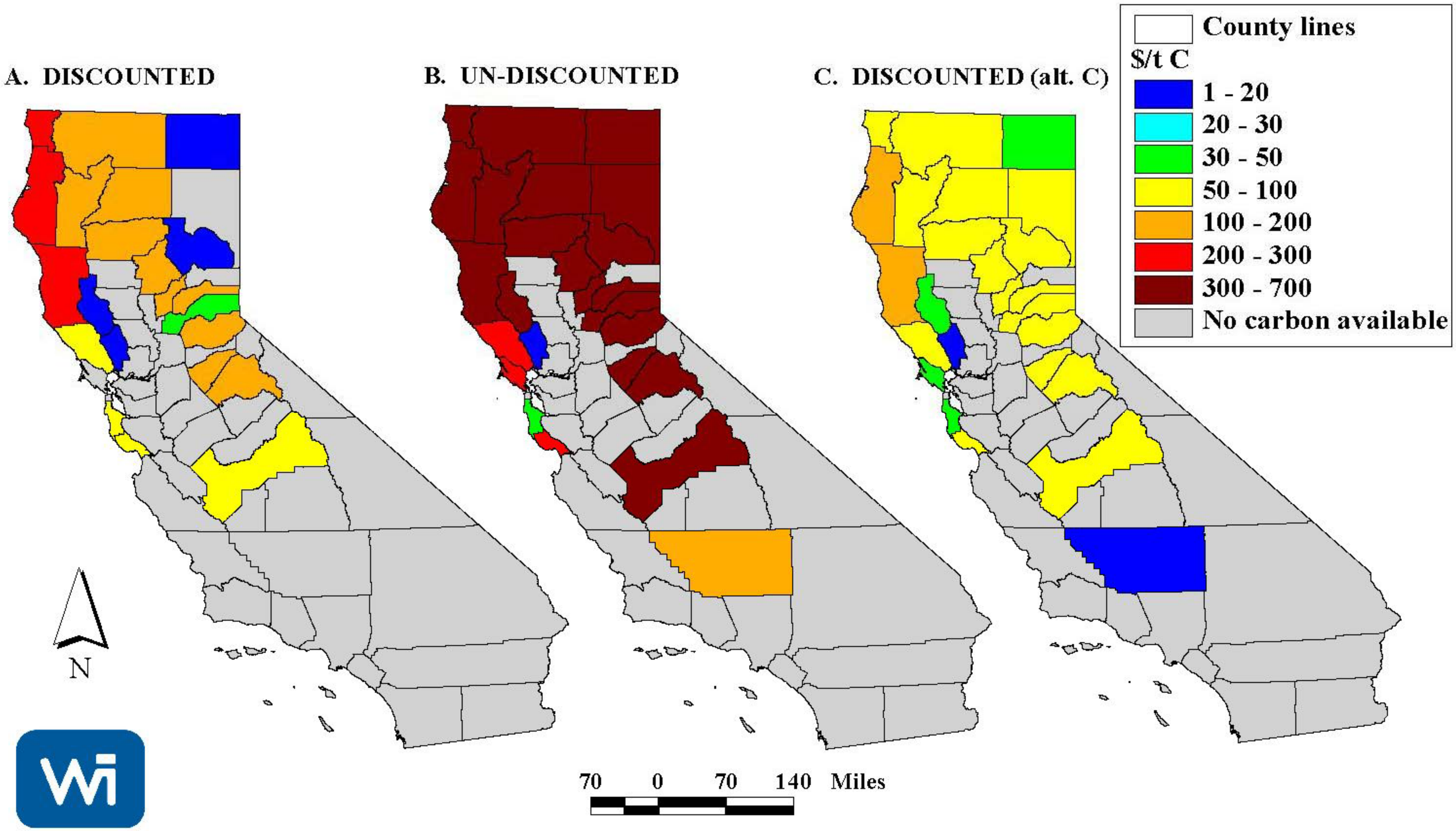

Figure 1-8. Distribution, at the county scale, of the cost to sequester carbon (in $/t C)with 20-year contracts via lengthening the forest rotation time by 5 years for A. discounted carbon, B. undiscounted carbon, and C. discounted carbon (for A. and B. see Tables 1-15 and 1-16, and for C. see Appendix A, Table A3 for details). To convert to $/short t CO_2, divide $/t C by 4.0.

For the three marginal cost curves, the lowest cost options are mainly with hardwoods, although there are some opportunities with fir spruce and Douglas fir in some counties. Hardwoods tend not to be heavily managed for commercial purposes, and these estimates assume hardwoods are managed for timber. Thus, the lower end of the marginal cost curve may reflect opportunities that are not available in reality. Costs tend to rise rapidly for the softwood species, which can be seen in the figures. These results are consistent with the analysis above in **Tables 1-8 through 1-13**.

1.3. Riparian Zone Management

The potential for riparian zone management to increase carbon sequestration arises due to the proposed widening of the existing buffer by 100 feet on each side of certain streams. These new buffers are essentially set-asides. They potentially represent substantial reductions in the area of forests available for harvesting. For harvest areas that include protected streams, the new set-aside could represent an additional 200 feet of forest for the length of the stream in the area harvested.

Estimating the potential carbon credits associated with these set-asides raises an important issue related to carbon crediting. Take for example the high site Douglas Fir discussed above harvested in 48-year rotations. **Figure 1-9** shows the carbon situation for a riparian zone set-aside (red line) versus harvesting that stand (blue line). For a stand that is initially 48 years old, if the stand is set-aside, carbon accumulates along the red line from the year of the set-aside forward. If stands are harvested, approximately 63 tons of carbon per ha are put into products, followed by a period of slow emissions as product decay outweighs growth of the new stand, followed by a period a rapid carbon accumulation and eventual harvest, and continuation of the cycle.

Under the assumptions of the aging scenarios discussed above, the baseline condition would provide credit for the product stored in wood products in the initial period when the stand is harvested. No such credit would occur for the remaining part of the stand that is maintained in the riparian zone, even though the initial 150 tons/ha in a 48 year old stand is essentially locked up forever (these are the same tons that created the forest products). The same carbon—the initial 150 tons—is treated differently depending on whether harvests occur, and specifically, the carbon is credited if stored in products, but not if stored on the landscape. A property right issue revolves around proper crediting of historical growth at the time the policy is enacted.

The property-right issue also affects the aging analysis above, although there it is less important because stands are assumed to be harvested regardless of their rotation age. By extending rotations, one still gets credit for past accumulation in that analysis, but the landowner has to wait some additional years to get the credit (note: This type of property right increases costs for individual landowners). In the case of the riparian zone analysis, if one counts the initial harvests for the baseline, but ignores the maintained stock for the riparian zone, then two different property rights are assigned.

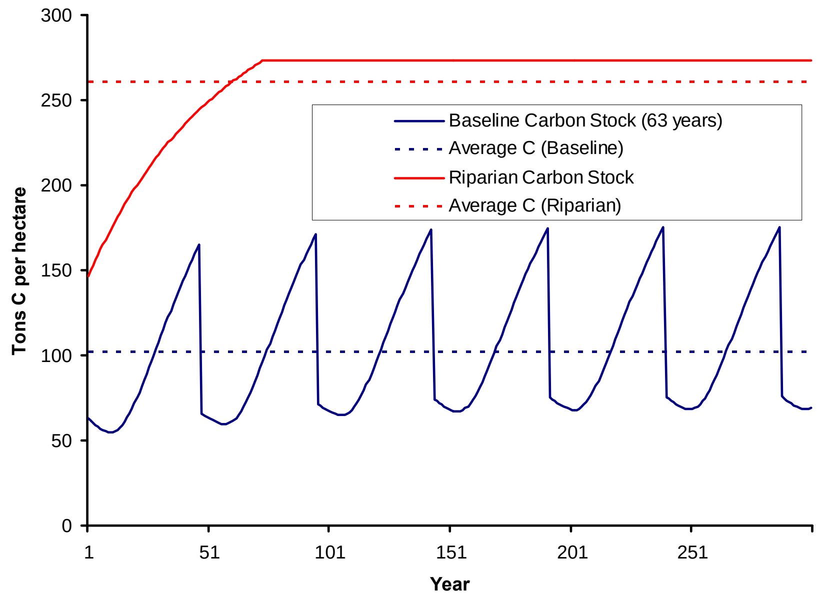

Figure 1-9. Tons carbon per hectare stored in above-ground biomass and products, assuming stands are initially 48 years old.

Table 1-17. Carbon values for high site Douglas Fir comparing baseline rotations to riparian zones

	Rotation Age 48	Age 48 to 300		Property right 1: Difference Between Rotations (c3 – c1)
	Value in PV Terms	Value at 300	Value in PV terms	
	c1	c2	c3	c4
(r1) t/ha	146.49	273.12		
(r2) tons stored in products (first harvest only)	62.99	0.00	0.00	
(r3) PV carbon stored in products	35.67	0.00	0.00	-35.67
(r4) PV carbon in future rotations	46.44		0.00	-46.44
(r5) Carbon in additional biomass growth	0	129.95	64.71	64.71
(r6) Sum (r3 + r4 + r5)	82.11	129.95	64.71	-17.40

Consider the example of the high site Douglas fir discussed above, the relevant values for the present value analysis are shown in **Table 1-17**. The first column represents carbon sequestration values for harvesting the stand in 48-year rotations. The second and third columns are the carbon sequestration values for holding the same land, starting at age 48 years, as a riparian zone. Under the property rights defined for aging above, the results are shown in Column 4. In this scenario, the following credits apply to the baseline: (1) carbon initially stored in products (35.7 tons per hectare), and (2) carbon stored in future rotations (46.4 tons per hectare). The following credits apply to the riparian forest: (1) new growth as stand ages (64.7 tons per hectare). The net is a loss of 17.4 tons per hectare when converted to a riparian zone.

As noted, this provides no credit for locking up carbon on the original site by not harvesting. To account for this difference, a simple correction would be to ignore the carbon stored initially in products. Ignoring this carbon would result in a comparison between the present value of future rotations in the baseline (46.4 tons per hectare) and the carbon in additional biomass growth for the riparian zone (64.7 tons per hectare). Using this calculation, there would be a net gain in carbon of 18.3 tons per hectare with a riparian zone rather than a loss.

With respect to the atmosphere, a third alternative is possible, one that accounts for emissions that occur during harvest. Such an alternative essentially penalizes harvesting by counting the emissions during the period when they are in the atmosphere. Harvesting does not lead to permanent emissions because most of the carbon in the atmosphere will ultimately be stored back in wood on the stump or in forest products. However, it does cause a temporary emission that causes damages for some time period. It is possible to account for these emissions by valuing them when they occur. Thus, under this third alternative, the difference in carbon stocks in the two cases is first estimated for each year in the future, and then the annual change in the difference in stocks is estimated. Referring back to **Figure 1-9**, the difference among the two alternatives is first estimated to get the annual stock differences, and then the annual change in the difference in stock is used to estimate the carbon gain for the riparian zone. Under this method, the present value of the carbon gain associated with the riparian forest is a substantial 123.2 tons per hectare. This estimate most closely approximates the net effect of the carbon change on the atmosphere, although the implication is that emissions at harvest will be penalized.

For the purposes of this analysis, estimates of carbon gains are provided for all three estimates for each region. METHOD 1 follows most closely the aging analysis, and was described first above. Carbon in harvests is credited if the stand is harvested, and new growth is credited if the stand is set aside. METHOD 2 ignores the initial harvest, and only credits future harvests after the first period of regrowth, and it credits new growth on the set-aside land. METHOD 3 compares the net stock in each case and then estimates the annual change in the gain in net stock for the set-aside. Depending on how the rules for crediting carbon sequestration eventually are written, any one of the methods may be most appropriate.

Tables 1-18 and 1-19 present cost estimates for riparian zone protection in California timber region 7, with **Table 1-18** presenting costs for lands otherwise harvested at economically optional rotation ages, and **Table 1-19** presenting costs for lands otherwise harvested at legally mandated rotation ages. As one can see, under carbon accounting METHOD 1, carbon flows are negative in nearly all regions, with the exception of Fir-Spruce and redwood. METHOD 1, recall, credits only timber that is harvested and stored initially, but does not credit timber already held in forests that are set-aside.

Under METHOD 2, there are positive opportunities for carbon sequestration in a number of species, particularly for the rotation ages suggested under the economically optimal scenarios.

METHOD 2 simply ignores carbon stored in forest products for the first rotation, thereby ignoring the initial stock. Under METHOD 3, there are positive opportunities for carbon sequestration in all scenarios. It most closely represents the influence of the policy on the atmosphere, although it assigns rights to past carbon sequestration efforts (i.e., historical timber growth) in both cases.

While these methods estimate carbon sequestration in forests that are set-aside, they ignore potential leakage effects. Leakage could occur if landowners simply increase the overall size of the areas they propose to cut in order to compensate for the set-asides. The extent of this potential leakage has not been estimated here, but should be considered as part of carbon sequestration plans.

Table 1-18 (*Permanent Contract – Discounted Carbon*). Net carbon sequestered and $ per ton, using three different methods (see text), for setting aside economically mature forests permanently in California timber region 7.

	t C per hectare			$ per t C		
	Method			Method		
	1	2	3	1	2	3
HWD Hi	-37.18	-16.01	66.26	--	--	$43
HWD Med	-5.30	10.28	66.59	--	$231	$36
HWD Low	-1.95	6.10	34.88	--	$197	$34
DF Hi	-18.46	17.21	123.15	--	$1,237	$173
DF Med	-26.96	2.31	89.65	--	$7,097	$183
DF Low	-25.96	-4.01	60.23	--	--	$190
PP Hi	-12.02	10.95	80.26	--	$1,223	$167
PP Med	-18.27	-1.24	50.38	--	--	$169
PP Low	-15.93	-2.16	39.42	--	--	$155
FS Hi	7.46	27.69	86.74	$751	$202	$65
FS Med	-1.04	9.68	42.54	--	$257	$58
LP Avg.	-17.32	-2.44	42.89	--	--	$163
RW Hi	-1.97	24.03	101.93	--	$982	$231
RW Med	-39.23	-10.35	76.85	--	--	$347

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

Table 1-19 (*Permanent Contract – Discounted Carbon*). Net carbon sequestered and $ per ton, using three different methods (see text), for setting aside mature forests at legal harvest ages permanently in California timber region 7.

	t C per hectare			$ per t C		
	Method			Method		
	1	2	3	1	2	3
HWD Hi	-67.06	-38.39	57.27	--	--	$99
HWD Med	-25.84	-4.55	65.96	--	--	$62
HWD Low	-12.55	-1.53	34.92	--	--	$57
DF Hi	-24.34	12.90	123.53	--	$1,728	$180
DF Med	-35.66	-4.02	90.38	--	--	$197
DF Low	-39.61	-14.03	62.49	--	--	$215
PP Hi	-12.02	10.95	80.26	--	$1,229	$168
PP Med	-21.01	-3.20	50.66	--	--	$179
PP Low	-23.88	-7.70	40.82	--	--	$186
FS Hi	-15.85	10.90	89.84	--	$692	$84
FS Med	-14.63	0.35	44.84	--	$10,594	$82
LP Avg.	-26.52	-8.99	43.80	--	--	$198
RW Hi	2.13	26.84	101.07	$10,540	$835	$222
RW Med	-68.81	-32.08	78.11	--	--	$444

HWD = hardwood species; DF = Douglas fir; PP = ponderosa pine; FS = fir-spruce; LP = lodgepole pine; RW = redwood; Hi= high site quality; Med = Medium site quality; Low = low site quality; Avg =average site quality.

These estimates of costs can be aggregated to determine the total costs of the extending the riparian zone, and the potential carbon savings. To aggregate these estimates, we first estimate the total length of perennial streams with data from the California Spatial Information Library (2004). Perennial stream lengths within the forest types listed in **Table 1-19** above are then estimated for each county. It is not possible to determine the average site quality in these regions, or the average age class, so we use FIA data for the county and assume that the county estimates are representative of the land near perennial streams.

For each mile of stream length, we assume that an additional 200′ of land will be preserved, and we assume that all land near the optimal rotation age will be harvested in the near future. Using these pieces of information, we can estimate the total area of land within an additional 200′ of streams that is close to the optimal rotation age in each forest type. With this information, it is possible to use METHODS 1, 2, and 3 as discussed above to estimate carbon potentially sequestered in these areas.

The estimates are shown in **Table 1-20** and **Figure 1-10** (using METHOD 3). Total stream reach in miles is shown, along with additional riparian area. The area of this riparian zone that is near optimal rotation is shown in the third row of **Table 1-20**. Assuming all of this land would otherwise be harvested in the near future, the amounts saved according to each method are shown, as well as the total costs. Note that using METHODS 1 and 2, the carbon would be estimated to be emitted with the riparian zone analysis. METHOD 3, however, shows the impact of extending the riparian zone on the atmosphere. Using method 3, the average cost of conserving the carbon in the extended riparian zone is \$71/t C for public lands and \$96/t C for private lands (**Table 1-20**).

Table 1-20. Estimated stream reach, additional riparian area, mature additional riparian area, quantity of carbon in mature areas, and total costs of riparian area protection for a 200' extension of riparian zones.

	Public	Private
Total Stream Reach (Miles)	32,058	32,516
Total Additional Riparian Area (Hectares)	314,681	319,170
Additional Riparian Area Near Rotation (Hectares)	19,136	27,849
Tons C if all harvested (1000 t)		
Method 1	0.4	3.4
Method 2	72.0	112.0
Method 3	1,167	1,771
Total Cost if all to be Harvested (1000 \$)		
Method 1	\$4,558	\$24,122
Method 2	\$103,365	\$50,422
Method 3	\$83,190	\$169,948

On public lands, the least expensive carbon, less than \$70/t C (or less than \$17.50/short ton CO_2) generally coincides with those counties that potentially provide the highest quantities (Northeast Cascades and the northern part of North Sierra). On private lands, the trend is roughly the same, except the most carbon at the least expensive cost is mainly centered in Northeast Cascade counties (**Figure 1-10**).

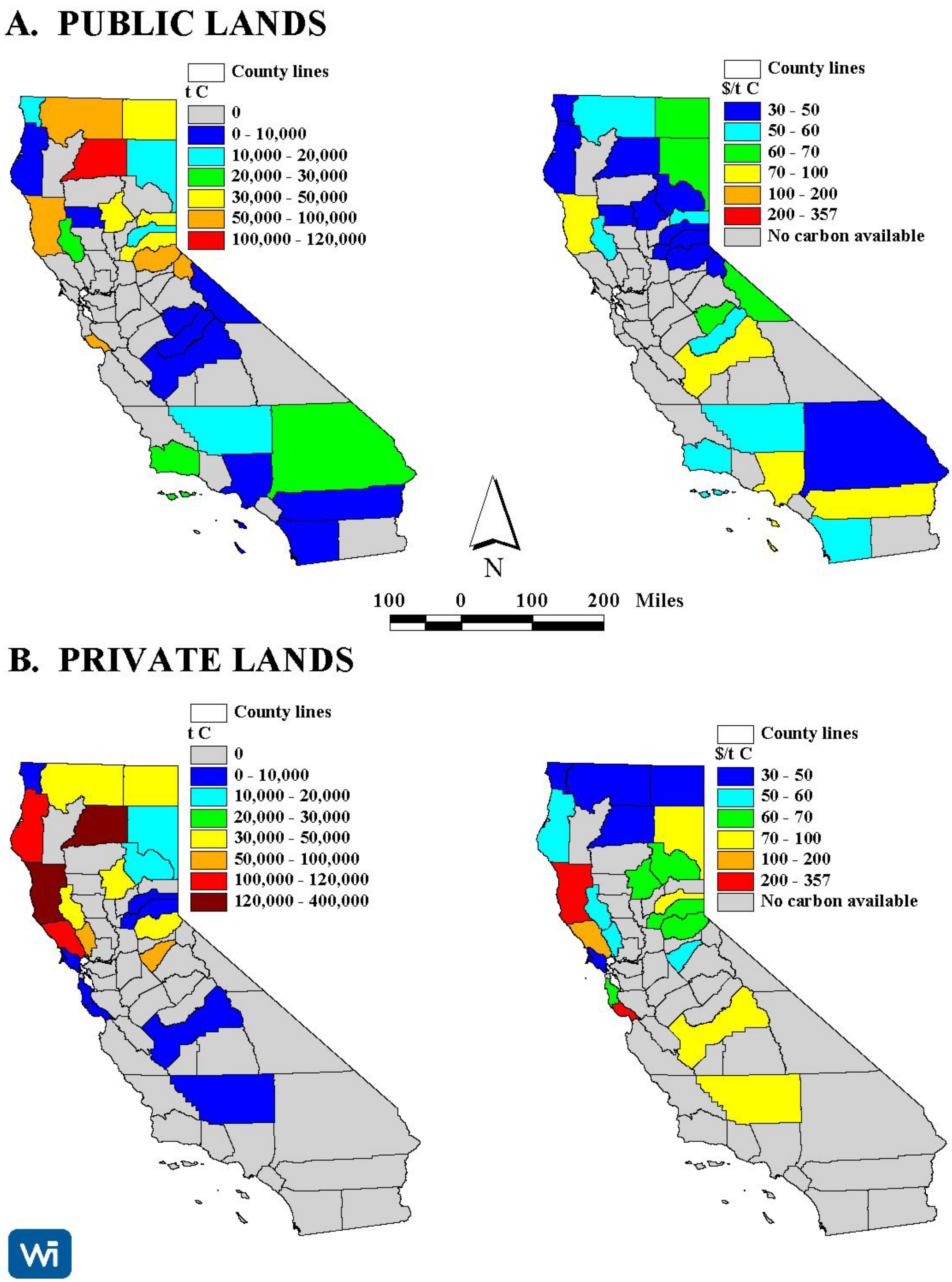

Figure 1-10. Distribution at the county scale of the quantity and cost of sequestering carbon by extending riparian buffers 200 feet along perennial streams on public and private lands.

1.4. Group Selection Harvests

An alternative method to potentially sequester carbon involves group selection cuts. Group selection cuts involve harvesting in smaller areas than traditional clear cuts. In the field measurements module at Blodgett forest in the north Sierras, traditional clear cuts are suggested to be 8 hectares (20 acres), and group selection cuts are proposed to be 0.6 hectares (1 acre). That study compares a set of group selection cuts that equal the overall size of an 8 hectare clearcut, i.e., 13 group selections roughly equals 8 hectares.

The analysis for Blodgett forest showed essentially very little to no carbon gains associated with the group selection cuts relative to the clear cuts. Forest regrowth within large clear-cut areas is substantially faster than forest regrowth within the smaller group-selection cuts (due to shading). The results focused on ponderosa pine, however, and the use of more shade tolerant trees may have carbon gains associated with group selection cuts.

The main economic issues related to group selection cuts revolves around the costs of harvesting. Larger clear cuts are usually cheapest on a per unit harvested basis due to economies of scale of the operation. Foresters have to spend less time moving equipment from site to site, moving equipment and logs through forested areas, and moving labor from place to place. Further, on some sites that are only suitable for cable yarding, group selection cuts may be particularly costly due to the logistics of setting up cables and choosing locations for the group selection cuts.

For the purposes of this analysis, no estimates of carbon gains are made. Instead cost differences among alternative harvest regimes are presented to provide estimates of the potential increases in costs associated with group selection cuts. The costs are provided for different species, using average information from USDA FIA data on biomass available for harvests. The examples for this section follow the two examples analyzed for the Blodgett forest, namely:

> *(1) Group Selection Cuts*: 8 hectares are harvested in total in 13 different 0.6 hectare clear cuts within a 24 hectare area
>
> (2) *Clearcuts:* 8 hectares harvested contiguously.

This analysis assumes that the group selection cuts are set up for optimal economic harvesting within the context of the group selections. For example, the paths to be used for extracting timber from the woods to the landing site uses the most suitable pathway, or the cable yarding systems can be set up in an economically optimal fashion. Further, it is assumed that the trees in each of the group selections are similar to the other group selections.

To conduct this analysis, software (STHarvest) developed by Fight et al. (2003) at the USDA Forest Service Pacific Northwest research lab was used. The database for the software relies on an extensive review of harvesting systems and harvesting costs used in the western United States reviewed in Hartsough et al. (2001). Functions for harvesting different types of forests are estimated and used within the model. In this analysis, only ground-based manual logging systems and cable manual systems are considered.

Forest harvesting operations basically have the following steps: (1) cut the trees; (2) skid or yard them to a landing; (3) de-limb, de-bark, and other processing; and (4) load and haul the logs away. These operations can be conducted with a wide variety of machinery, and by individuals of many different skill levels. The cost estimates shown in this study are averages that provide some indication about potential cost levels, but they do not indicate costs for any particular site.

Costs will also vary by the size and volume of trees on the site. For the purposes of this study, size and volume estimates have been developed from the USDA Forest Service FIA data for private lands in age classes 50 – 250 years (**Table 1-21**). All values in this section are listed initially in traditional units of measure, and later converted to metric units. For softwood species, average individual tree sizes range from 35 (ponderosa pine low site) to 77 cubic feet per tree (redwood high site). Only trees greater than 11″ diameter at breast height (DBH) are included in the calculation of average tree diameter. The number of trees per acre ranges from 351 to 493 for all trees and 109 to 256 for trees greater than 11″ DBH.

Analysis with STHarvest requires estimates of the average volume and number of trees for the cutting sites. Costs estimates were developed for the following ranges of harvesting: Average tree sizes = 30, 50, and 70 ft^3; Average cut trees per acre = 100, 150, 200, and 250; slopes 10% and 40%. While costs do vary across these ranges, cost differentials between group selection cuts and clear cuts did not vary substantially. As a consequence, only the results for an average stand are presented. The "average" stand is assumed to have a tree average of 50 ft^3 and 150 trees per acre.

Table 1-21. Average tree size and trees per unit area for private lands in California

		Cubic feet sawtimber per tree (Trees > 11″ DBH)	Trees per acre (All Trees)	Trees per acre (> 11″ DBH)
Douglas Fir	High Site	61	359	67
Douglas Fir[1]	Med Site	62	493	54
Douglas Fir	Low Site	41	351	68
Ponderosa Pine	High Site	53	357	62
Ponderosa Pine	Med Site	45	435	63
Ponderosa Pine	Low Site	35	374	44
Fir/Spruce	Med Site	56	422	54
Fir/Spruce	Low Site	40	487	76
Lodgepole	Total	41	362	61
Redwood	High Site	77	458	103
Redwood	Med Site	71	355	92
Hardwood	High Site	57	473	64
Hardwood	Med Site	42	489	60
Hardwood	Low Site	38	379	37

(Source: USDA FIA data)

[1] For the medium site class Douglas Fir, 30% of the private growing stock was classed in 41″ diameter trees and larger. These were removed from the estimated average cubic foot sawtimber estimate.

Table 1-22 presents average results for the difference in costs between an 8 hectare clear cut and an 8 hectare partial cut for the average stand listed above. The same amount of wood is cut in each case, however the costs for the partial cut are higher due to the increase maneuvering costs associated with felling and skidding. Note that no chipping was assumed for these stands.

For the 10% slopes, cost differences average \$4.26 per 100 ft^3, with the cheapest costs in the cut-to-length system. Cost differences rise for the higher 40% slopes, averaging from \$6.04 per 100 ft^3. Although not shown, the results do suggest that harvesting cost differences are larger for smaller diameter trees. The example in **Table 1-21** is for trees that are on average 50 ft^3 in volume. For trees that are 70 ft^3 on average, the average reduction in cost is 9% for 10% slopes and 15% for 40% slopes. For trees that are 30 ft^3 on average, the average increase in costs is 19% for 10% slopes and 29% for 40% slopes. There are substantial cost penalties associated with harvesting smaller stands and smaller diameter trees on average. The largest cost penalties accrue to the cut-to-length harvesting systems.

Table 1-22. Total costs for manual logging operations on 10% and 40% slopes in California (50 ft^3 average tree size, 150 trees per acre; 20 acre site).

	Manual Log	Manual Whole Tree	Mechanical Whole Tree	Cut-to-Length	Average
			\$ per 100 ft^3		
Manual Logging, 10% slope, Clear Cut	\$38.74	\$31.22	\$22.61	\$38.11	\$32.67
Manual Logging, 10% slope, Partial Cut	\$45.91	\$36.68	\$25.95	\$39.17	\$36.93
Difference	**\$7.18**	**\$5.46**	**\$3.34**	**\$1.05**	**\$4.26**
Manual Logging, 40% slope, Clear Cut	\$48.02	\$39.50	\$29.30	\$45.00	\$40.45
Manual Logging, 40% slope, Partial Cut	\$57.85	\$47.51	\$34.36	\$46.25	\$46.49
Difference	**\$9.84**	**\$8.01**	**\$5.06**	**\$1.24**	**\$6.04**

The STHarvest software application does not provide data on the specific layout of the partial cuts, although the software contains results from several studies that were conducted on group selection cuts, shelter-wood cuts, or different types of selection harvests. A different way to use the model to estimate the cost difference is to compare the costs of an 8-hectare clearcut to a 0.6-hectare clearcut. This analysis was conducted with the software as well. Using this method, the cost difference between these alternative size clear cuts for a stand with 150 trees averaging 50 ft^3 is \$21 per ft^3. Although this method represents an interesting example, it is likely to be a very high estimate, outside the range of reality. This occurs because the largest cost differences arise from fixed costs that are counted multiple times for the group selection cuts, but which likely would not have to be included multiple times since the group selections would be located relatively close to each other. Thus, the range of \$3–\$10 per ft^3 in **Table 1-21** is likely to capture most of the cost differences.

These cost differences are for cubic feet saw timber material taken off a site. They can be converted to growing stock volume in m^3 through the following conversions. First, the average saw timber proportion of growing stock volume in California stands above 50 years old is 88%. Second, there are 0.0283 m^3 per ft^3. The appropriate conversion is:

$$\$ \text{ per } m^3 = \$ \text{ per } 100\ ft^3 \times (1/0.0283) \times (1/0.88) \times (1/100)$$

Thus, the approximate range of cost differences between a clear cut and a group selection cut, when converted to growing stock volume on the site is approximately \$2.03 per m^3 for 10% slopes and \$2.88 per m^3 for 40% slopes with manual logging. Costs could be substantially higher for smaller trees, as noted above. Put into the context of the stumpage prices shown in **Table 1-5**, these cost differences are not all that substantial.

To consider the carbon implications of these costs, the question is how much these costs vary for entire sites. The cost differences comparing group selection cuts to clear cuts are shown in **Table 1-23** for 10 and 40% slopes. As shown in the Blodgett study, there is not likely to be much increased carbon sequestration with group selection cuts, however, if alternative sites show carbon gains, the results in **Table 1-22** can be used to estimate costs by comparing the values in **Table 1-22** with the carbon gained on the site.

Table 1-23. Cost differences between group-selection cuts and clear cuts.

Type	Site Quality	Cost Difference for 1 hectare harvested	
		10% slope	40% slope
Douglas Fir	High Site	\$397	\$548
Douglas Fir[1]	Med Site	\$326	\$449
Douglas Fir	Low Site	\$297	\$437
Ponderosa Pine	High Site	\$330	\$468
Ponderosa Pine	Med Site	\$305	\$449
Ponderosa Pine	Low Site	\$166	\$245
Fir/Spruce	Med Site	\$306	\$434
Fir/Spruce	Low Site	\$328	\$483
Lodgepole	Average	\$262	\$387
Redwood	High Site	\$739	\$988
Redwood	Med Site	\$613	\$820

Alternative estimates of the costs differentials between clear cuts and partial cuts have been obtained through personal communication with Douglas Wickizer (California Department of Forestry, 2004, pers. comm.). Those estimates suggest that partial cuts are approximately \$3 per m^3 (\$15 per MBF) more expensive than clear cuts on traditional tractor logging, and \$2 per m^3 (\$10 per MBF) more expensive with cable logging. These compare quite closely to the estimates from STHarvest presented above.

These results also suggest that the cost differences are less important on higher slopes (>40%) where only cable logging is appropriate. There are still positive cost differences with selection cuts on high slopes, but the cost differences are reduced. STHarvest did not support considering this option because of the limited number of studies investigating cable-logging equipment included in the software.

1.5. Forest Fuel Reduction

Management of wildland fire has been an important aspect of U.S. forest policy since 1872, when the first national park, Yellowstone, was established (Nichols 1989). It was a time leading up to the United States Forest Service (USFS) adopting a "fast, energetic and thorough suppression of all fires in all locations" policy in 1937 (Chase 1989). Instead of having a healthy fire return interval of every 15 to 20 years in landscapes similar to Yellowstone, accumulated woody fuels created an unnatural fire regime where infrequent, but intense fires threatened the natural state of many landscapes (Pyne et al 1996).

The United States has been plagued more by massive misdistribution of too much wildfire, too little controlled burning, too much combustion, and too little fire (Pyne 2000). Thus it has been seen as beneficial to use management-ignited fires as a method of restoring the historic fire return interval (Miller & Yool 2002). More recently, however, fire experts are debating that as carbon emissions and particulates from fire become more regulated, alternative methods to widespread prescribed burning will need to be investigated more thoroughly.

Fires appear to be increasing in size and intensity during the last decade, resulting in amplified loss of carbon stocks and billions of tax dollars are spent each year towards control efforts (**Figure 1-11**). As reported by the National Interagency Fire Center (NIFC) in Boise Idaho, 103,387 fires consumed 4.5 million acres in 1960. By the year 2000, 122,827 fires burned almost twice as much—8.4 million acres—while federal expenditures rose from $845 million in 1994 to $1.7 billion in 2002 (**Figure 1-12**). Although the official figures for 2003 expenditures in California have not been compiled, 9,116 wildland fires burned 793,402 acres and 738 prescribed fires burned 67,782 acres. The number of naturally ignited wildland fires managed to accomplish specific pre-stated resource management objectives in predefined geographic areas (outlined in the Fire Management Plans—WFU fires) were 126 consuming 41,069 acres.

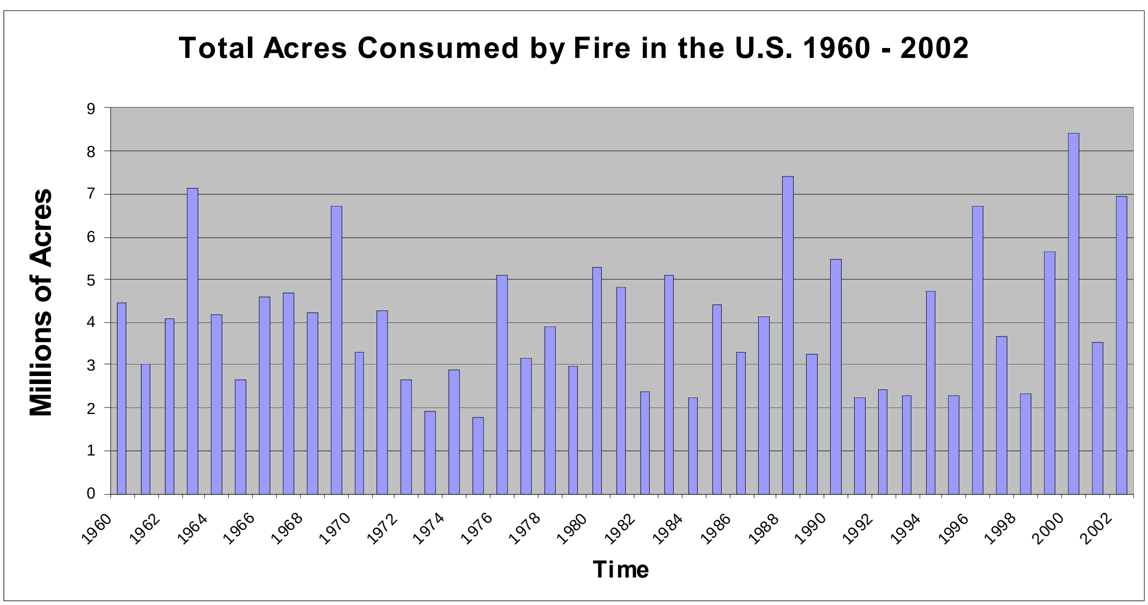

Figure 1-11. National Interagency Fire Statistics showing the area burned by wildfires in the U.S. from 1960 to 2002.

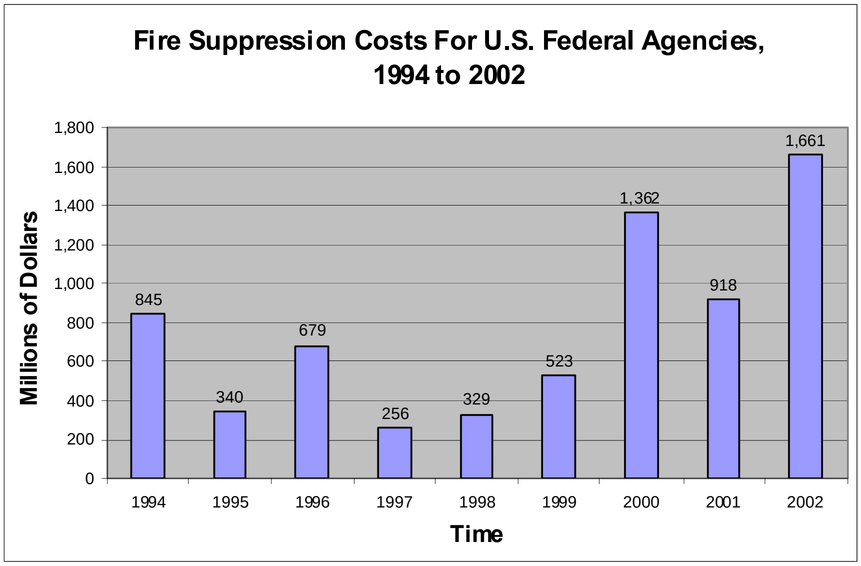

Figure 1-12. National Interagency Fire Statistics showing federal expenditures in millions of dollars from 1994 to 2002.

Fire occurrence has a significant effect on the amount of carbon in California's forested areas (EPRI 2004). Fire management techniques that reduce carbon emissions by reducing the risk of conflagrations through removal of fuels potentially offer another opportunity to supply carbon credits. A recent study in Southern Oregon investigated the viability of fuel treatment and biomass generation under a range of product prices and silvicultural practices aimed at reducing fire hazards (Fried et al. 2002). The following research questions were addressed: can fire risk be reduced, how much of the landscape could be feasibly treated, will there be enough biomass to fuel a power plant, where are the best places to site a power plant, and would a subsidy help. This study did not, however, consider the potential benefit of carbon credits.

A parallel study conducted by the University of California, Davis developed a GIS tool with the objective of estimating supply curves for forest thinnings and residues to biomass facilities by (1) reducing uncertainty in the amounts of available biomass at specific locations over the range of delivered price, making development of new energy plants more attractive, (2) escalating use of forest biomass for energy while expanding employment in rural forest areas, (3) moderating adverse effects of not using biomass for energy caused by stand replacing wildland fires, and (4) reducing cost of energy produced from forest biomass through available GIS technologies to locate suitable areas for new power plants (Chalmers et al. 2003). Although the UC Davis research team members addressed their goals, the scope covered only one county (Plumas County) and did not examine the potential economic benefits of using alternatives to fossil fuels for producing electricity.

Neither of the two studies above considered fuel reductions to reduce forest fire hazard and subsequent use for energy production as an activity for carbon credits. Not only would reductions in catastrophic forest fires reduce carbon and non-CO_2 GHG emissions from burning, but the use of the biomass to generate electricity would offset the use of fossil fuel emissions. The objective of this section is to estimate the areas and carbon stocks of forests suitable for fuel reduction to reduce their fire risk and their location relative to existing power plants. This analysis incorporates a Suitability for Potential Fuel Reduction (SPFR) score on forest landscapes where significant carbon loss from wildland fires exist. Additionally, SPFR scores are designed to rank areas feasible for transporting the removed fuels to biomass power generating plants.

1.5.1. Approach

The general approach is similar to the work on identifying grazing land areas suitable for afforestation activities (outlined in Section 2 of this report). The SPFR scores were created with a multi-criteria evaluation (MCE) technique in a GIS using slope, distance to biomass plants, and distance from roads as equal weighted factors in the decision making process. The MCE is a process of aggregating multiple layers to yield a single output map showing the suitability of land, and in this case, for SPFR scores (Eastman 2003).

The first step of the analysis was to locate forested areas at high risk to stand replacing wildland fire. A CDF-FRAP 2002 land-cover map was used to extract forested areas and the new layer was called, "forest." That layer was combined with a second FRAP fuel rank layer and used as a mask for the purpose of focusing on forested areas at high risk to fire. The FRAP fuel rank layer was derived by using detailed surface fuel layers and information based on quantities of ladder and crown fuels (CDF-FRAP 2004). For additional information of the land cover/fire data and methods, refer to the metadata downloadable from the FRAP website. Non-fuel and moderate classes from fuel rank were left out of the analysis while the high rank and very high rank attributes were combined with forest for use in creating a new layer called, "high risk forest" (**Figure 1-13**).

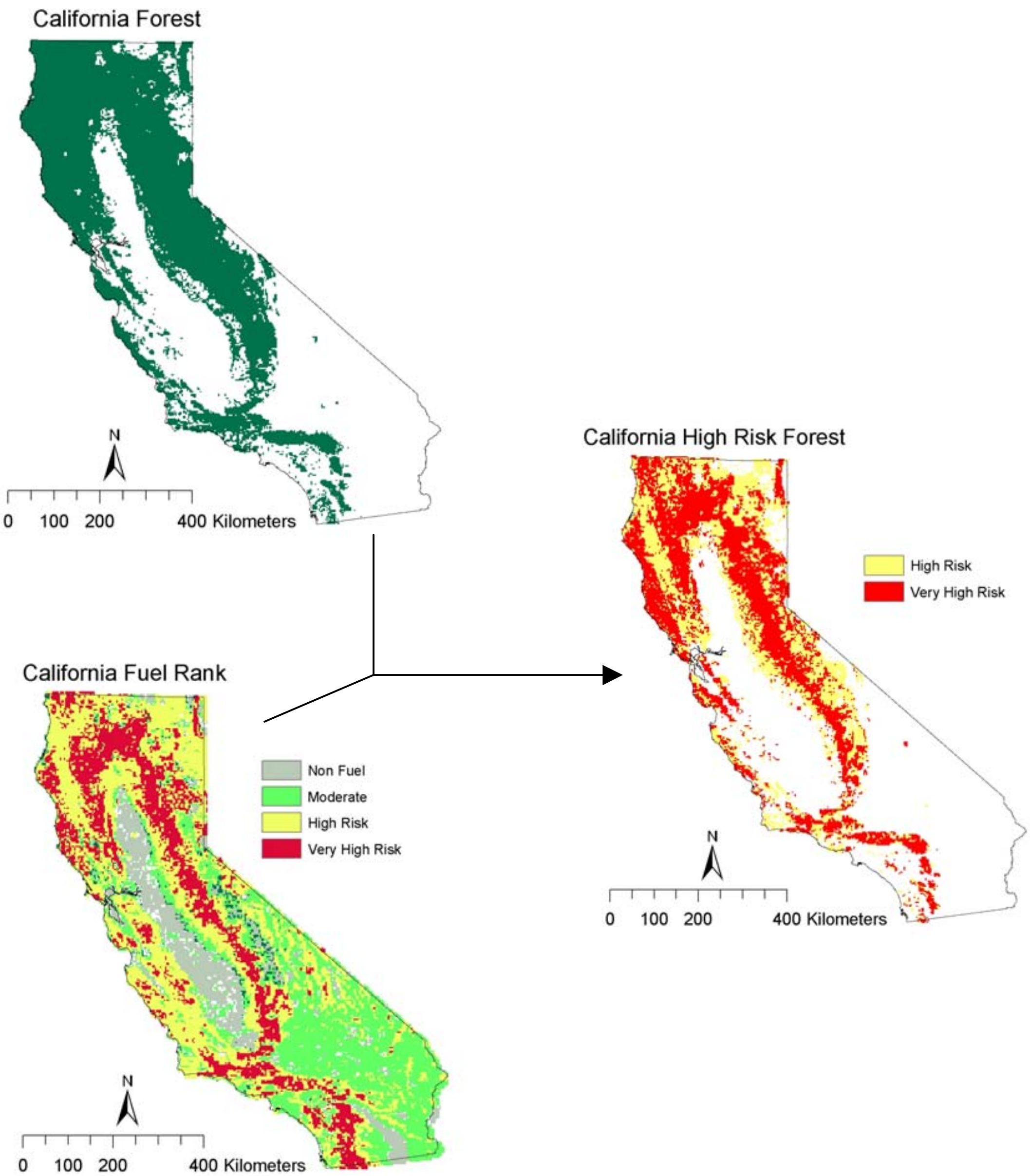

Figure 1-13. Distribution of California's forests at high and very high risk for catastrophic fire.

The second step of the analysis required production of factor images indicating the highest SPFR scores in identified high risk forest. The first factor analyzed was distance from roads. Six transportation related shapefiles (local_roads, railroads, state_highways, thoroughfare2, us_highways, and vehicular_trails) were downloaded from the CASIL web site and merged into one file called, "all_roads." A straight line Euclidean distance operator was applied to the roads layer and standardized using a fuzzy soft classifier for use in the MCE. California state law requires that all fuels within 100 meters of a roadway must be removed to reduce risk of fire (FRAP 2003). Therefore the starting point for most suitable areas began 100 meters from existing roads and became less suitable as distance from roads becomes greater (**Figure 1-14**).

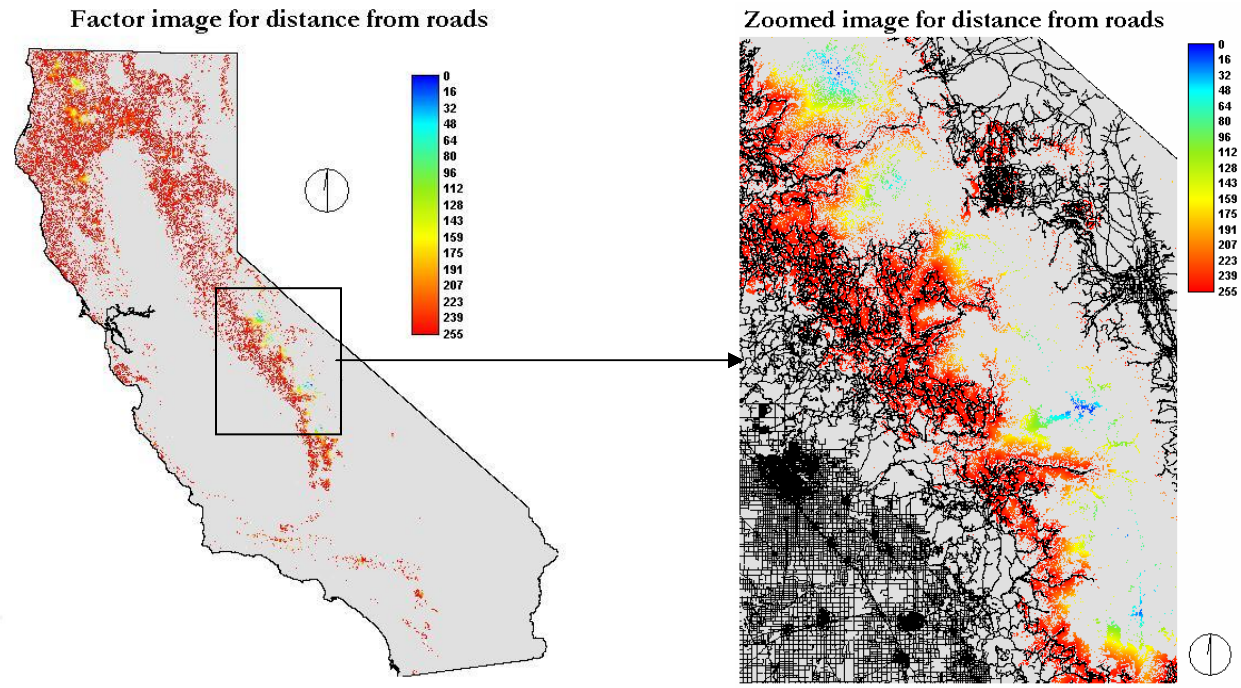

Figure 1-14. Factor image for distance from roads used in the MCE on a scale of 0 to 255 where 0 is the least suitable (furthest from roads) and 255 is the most suitable (closest to roads). The zoomed image shows greater detail in the database.

The second factor used in the MCE was slope. A slope image was created using a Digital Elevation Model (DEM) acquired from the CASIL web site and masked to the high and very high risk forest area of focus. The original slope map was in units of degrees but it was also standardized with a fuzzy soft classifier to give it a range of suitability between 0 and 255 where 0 would contain the most gentle slope or desirable value and 255 would indicate the steepest slopes or least desirable value (**Figure 1-15**).

A third criteria for assigning SPFR scores was distance from biomass electrical generating plants. An Excel file with locations of operational biomass power plants in California producing 0.1MW and above was provided by the California Energy Commission (CEC). The Excel file included fields for X and Y coordinates which were used to create a point file and added to the analysis maps. As with "distance from roads," a straight line Euclidean distance operator was applied to the locations of biomass plants and standardized with values of 0 to 255 where a 0 distance from biomass plants would be the maximum suitability and 255 would be the least suitable distance (**Figure 1-16**).

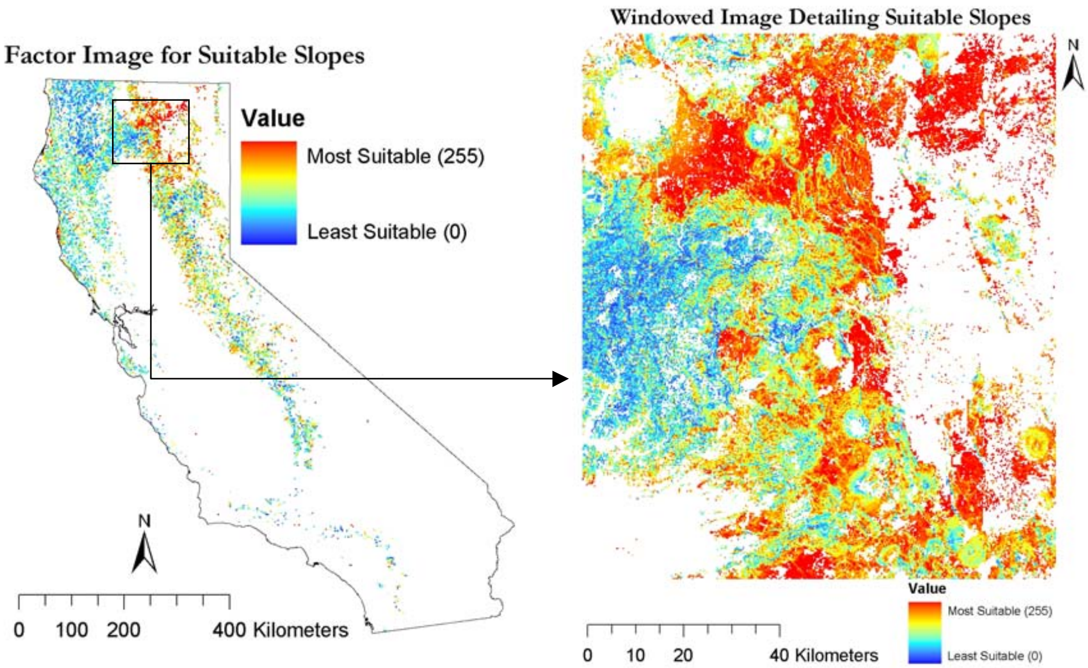

Figure 1-15. Slope suitability factor map and zoomed image detailing suitable slopes with zero value having the least SPFR scores and 255 the most SPFR scores.

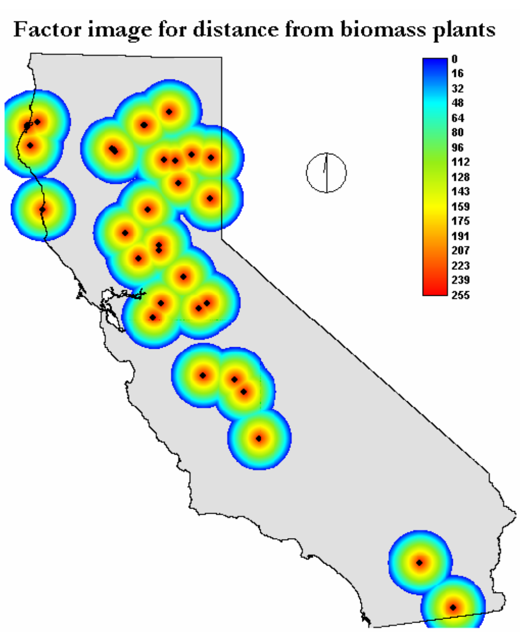

Figure 1-16. Suitability map showing distances from biomass plants where the highest SPRF scores are assigned to values close to the power generating plants.

Creating the three factor maps and converting them to standard scores provided the information needed to continue with the multi-criteria allocation decision processes resulting in final SPFR scores. As with the factor maps, the SPFR map is on a standard scale ranging from 0 to 255. where the low end of the scale represents the least suitable areas and the high end represents the most suitable areas for potential fuel reduction projects (**Figure 1-17**).

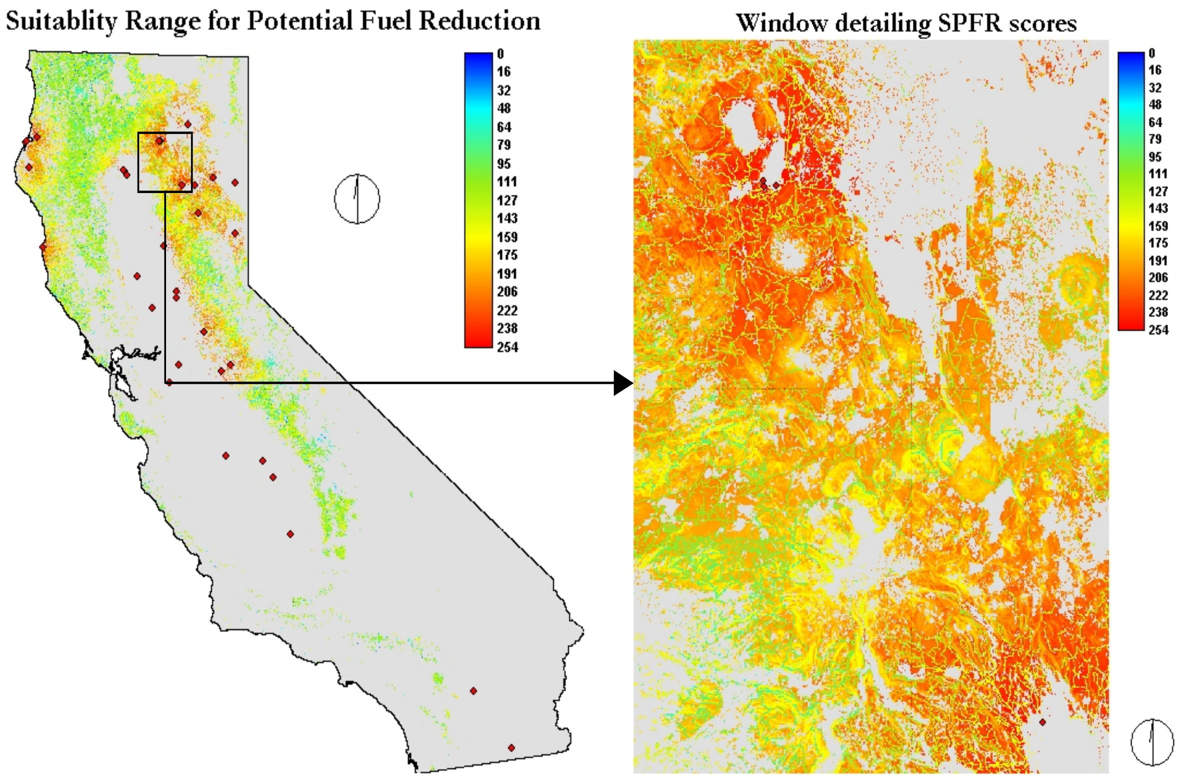

Figure 1-17. Suitability scores for potential fuel reduction with highest suitability assigned to areas with gentle grades of slope that are close to roads and biomass power plants.

The final objective was to determine the amount of land with the highest SPFR scores, relate them to carbon maps, and look at how fire reduction efforts may affect carbon stocks. The histogram of the area of forests in the final SPFR map shows that there are few forests in the low classes (less than 94), with the area increasing rapidly between 100 to 130 class, then gradually declining through the rest of the classes (**Figure 1-18**). For the analysis here, we arbitrarily used the upper 25% to be the cut off for “high suitability” to illustrate the methodology. The actual cut-off point requires further analysis as this point will be determined by economic analysis. The area of forests in the upper 25%, ranging in value from 190 to 255, accounted for 774,827 hectares of high suitability as most likely candidates for fuel reduction projects.

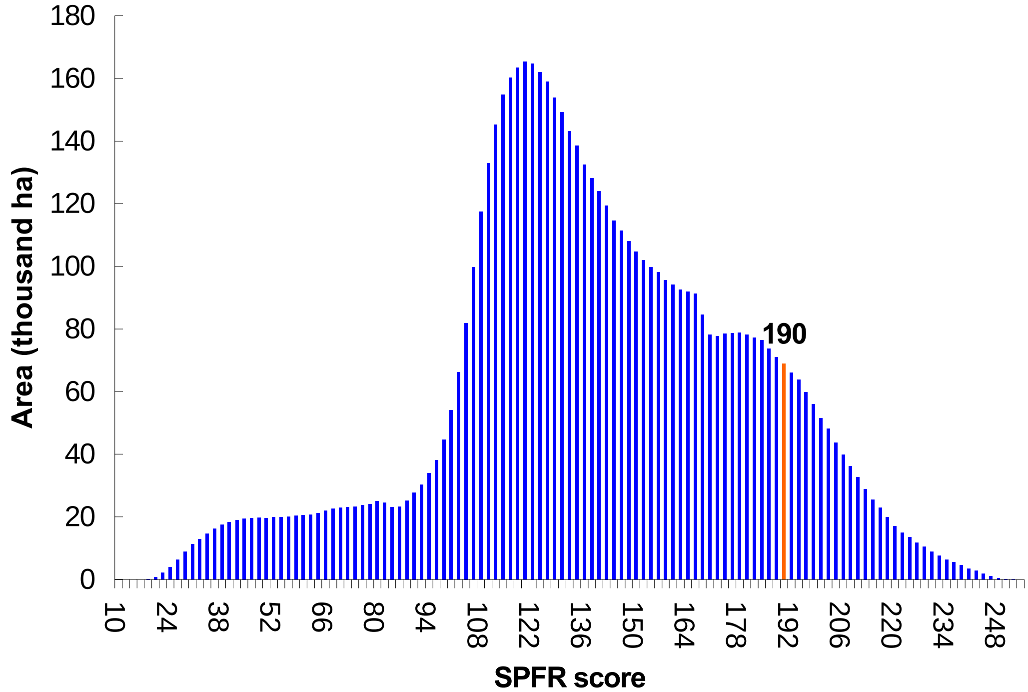

Figure 1-18. Area of forests at very high and high risk in each SPFR class. The score of 190 and above considered arbitrarily to be "high suitability" for fuel reduction because the forests are on gentle slopes, near a road, and near a power plant.

Across the state, the vegetation composition in the SPFR classes is predominantly "Other Conifer Forest" and "Hardwood Forest" with some "Fir-Spruce Forest," "Redwood Forest," and "Douglas Fir Forest" that decline in proportion to the others as the score gets higher (**Figure 1-19**). The "Other Conifer" class is expected as these are composed mostly of the pines that grow in highly fire prone areas and are some of the most fire resistant forests in California.

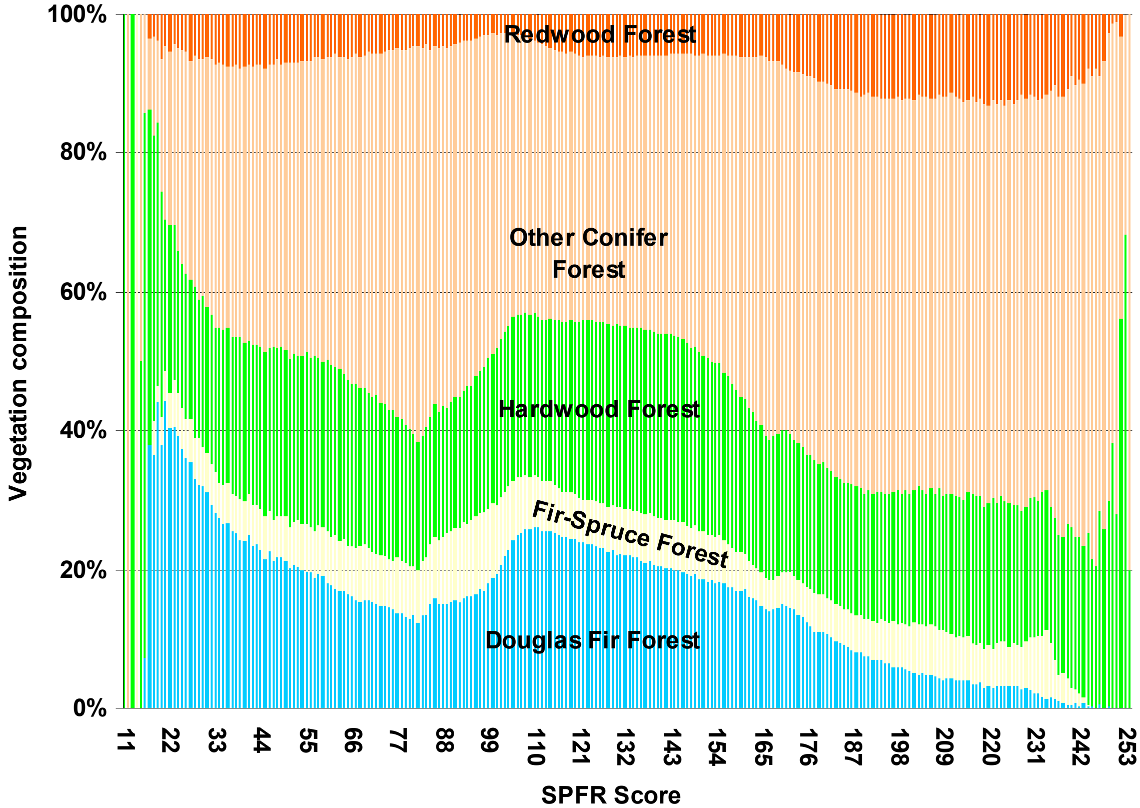

Figure 1-19. Forest composition of the SPFR classes for areas at high and very high risk for fire.

To estimate the carbon at risk for forest fires in these areas of SPFR, baseline carbon stocks were estimated within them. The FRAP Multi-source land-cover map that was used in the analysis contains attribute information for all Wildlife Habitat Relationship (WHR) land-cover classes mapped. In a parallel Winrock International study on baseline carbon emissions in California, a methodology was developed to estimate carbon stocks using a combination of these attributes (forest type and canopy coverage class [EPRI 2004]) (**Figure 1-20**).

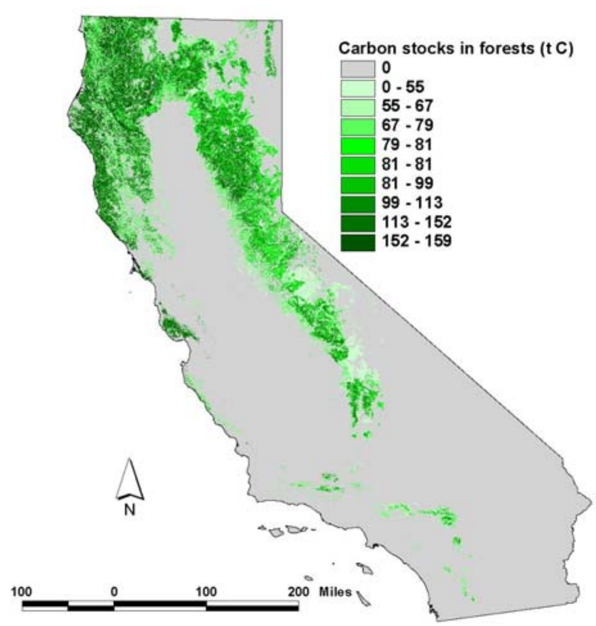

Figure 1-20. Map of carbon stocks for California forests.

From the baseline study (EPRI 2004), biomass carbon stocks were estimated for each canopy class and regrouped WHR classes. This matrix of carbon stock estimates was used with the reclassed WHR map to assign a carbon stock to each pixel. In areas where no information was given in the 'WHR-density' (canopy density) field, the value was conservatively estimated to be the lowest percent canopy-cover.

The carbon stocks map was superimposed on the SPFR map to determine the amount of carbon on the land classified with different SPFR scores. The carbon stocks that the model identifies as being at risk for wildfire for each level of SPFR are shown in **Figure 1-21**.

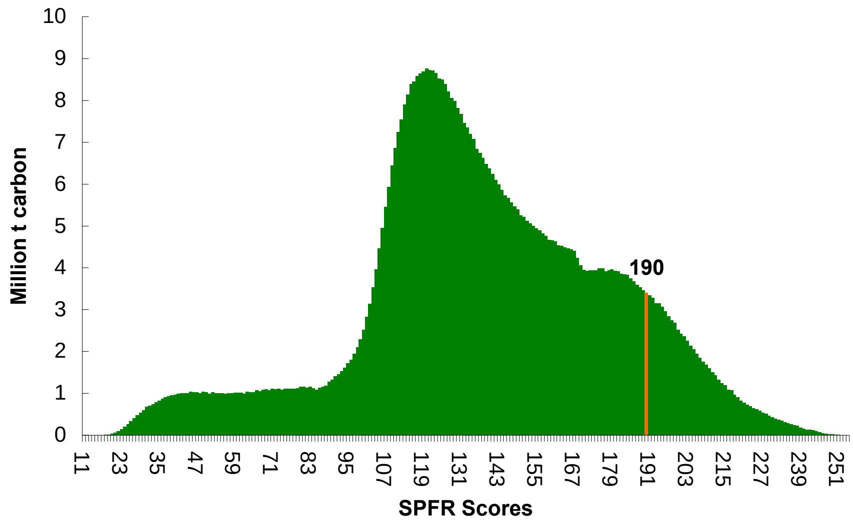

Figure 1-21. Carbon stocks by SPFR classes for forests at high and very high risk for fire.

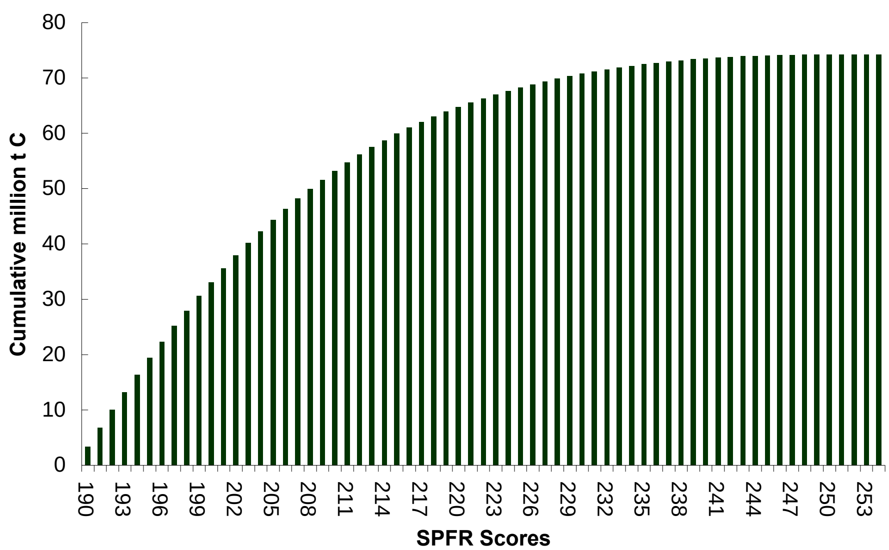

Figure 1-22. Cumulative carbon stocks in forests at high and very high risk for fire with a SPFR classes greater than 190.

For the top 25% of the SPFR classes, a cumulative total of 74.2 million t C is at risk for emitting carbon and non-CO_2 gases through forest fires (**Figure 1-22**) covering an area of approximately 775,000 hectares. Based on the baseline report (EPRI 2004), the estimated emissions from these forests if they burned could be as much as 23 million t C. Clearly the potential to reduce these emissions plus the inclusion of substituting fossil fuels with biomass could be an important component of California's strategy to mitigate GHG emissions. Further work is warranted, including economic analysis of the gathering and transportation of the biomass fuels, field data on effect of fires on carbon stocks, the pattern of recovery of carbon stocks after fire, and fuel substitution costs and efficiencies at the power plant.

1.6. References

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2.0 RANGELANDS

2.1. Rangelands of California

California, America's third-largest state encompasses 100 million acres (40.5 million ha) of land roughly comprised of 23% forests; 20% urban, agriculture, or aquatic landscapes; and 56% rangelands—including several woodland classes. Over 100 years ago, when California's booms in timber, gold, and silver had not yet attracted thousands into the region to exploit its forest resources, evidence suggests that in many places, large tracts of dense forest may have once stood where human populations, agriculture and grazing lands now do. We hypothesize that a significant proportion of today's oak woodlands and annual grassland vegetation types on California's rangelands were also once either dense forests or similar woodlands but with significantly higher biomass than they currently contain.

Presently, in much of the state, ranching is the primary activity on what remains of these lands that were once forests or woodlands (**Figure 2-1**).

Figure 2-1. Photographs of California rangelands.

California's beef industry is the state's fifth largest agricultural sector and California is the seventh leading beef producing state in the United States. The state has roughly 22,000 ranches, with a total of over 5 million head of cattle. California produces slightly over 5% of the nation's beef cattle. The state's beef industry is primarily cow-calf operations where young stock are raised on rangeland and then sent to Midwest feedlots for finishing (California Cattlemen's Association 2004).

With the potential for the development of a carbon market in California, there is an interest in determining how much carbon can be sequestered in the state and at what price landowners would be willing to convert their lands to other uses. If the price is right for stakeholders in these rangeland areas to invest in methods to increase woody biomass, carbon sequestration could be a lucrative business for them as well as one that contributes positively to global climate change mitigation, habitat conservation and restoration of the scenic California landscape.

2.2. Objectives of Study

To date, estimates of the carbon storage potential in the United States are of those based on simple biological and technical criteria without consideration of the economic costs associated with changing land management practices or of the varying carbon sequestration potentials across diverse landscapes. Incorporating the varying carbon sequestration potential of different land classes and other economic factors will yield more realistic estimates of carbon storage potential. Estimates of a more realistic potential for carbon sequestration from changes in land use can help companies prepare for an uncertain regulatory future by providing estimates of the quantity of carbon credits that might be available at different price points for different classes of activities.

The main goal of this section of the report is to generate a carbon supply curve for potential changes in the use of rangelands in California. Specifically:

1. Identify the area and current use and cover of existing rangelands
2. Estimate the area and geographic location of existing rangelands that could be afforested and the rates of carbon sequestration on the identified lands
3. Estimate the total cost of afforesting existing rangelands, including opportunity cost, conversion cost, maintenance costs, and measurement and monitoring costs
4. Estimate how many carbon credits will be offered at various prices for afforesting existing rangelands;
5. Determine the geographic distribution of available carbon credits at the various prices
6. Estimate associated risks and co-benefits

2.3. Methods

2.3.1. General Approach

The analysis incorporates information about current land use, potential changes in land use and the incremental carbon resulting from the change, opportunity costs, conversion costs, annual maintenance costs, and measurement and monitoring costs. The analysis is performed in a geographic information system (GIS) to include the diversity of existing land cover, rates of carbon sequestration, and costs in the analyses. As a result, not only are more realistic estimates of the potential supply of carbon produced, but the use of GIS shows where the least to most expensive carbon credits will most likely be found.

The general approach was to identify and locate existing rangelands where there is potential to change the use to a higher carbon content, estimate rates of carbon accumulation for each major potential land-use change activity, assign values to each contributing cost factor, identify datasets and methods to estimate risks, and identify datasets and methods to estimate co-benefits.

This study used a wide variety of spatial and non-spatial data sets. The spatial data include:

- California Spatial Information Library's 30-m DEM grids (derived from 1:24,000 Digital Elevation Models (DEMs) developed by USGS);
- NRCS STATSGO soil survey maps and databases and resultant analyses by non-NRCS researchers (Schwarz and Alexander 1995; Miller et al. 1998);
- USDA Forest Inventory and Analysis database;
- DAYMET Mean Annual Temperature map(Thornton et al. 1997);
- California Spatial Information Library's Precipitation maps (derived from USGS, California Department of Water Resources and California Division of Mines map and information sources);
- California Department of Forestry's Fire and Resource Assessment Program's (CDF-FRAP) 2003 Multi-source land-cover map and land ownership map.

Non-spatial data include, for example, regression equations for converting U.S. Forest Service Forest Inventory and Analysis (FIA) data to biomass carbon, forest growth models, published literature, experience from other Winrock activities, and state and county reports of agricultural statistics. The details of these non-spatial data are given in the appropriate sections below.

To capture all of California in one map with manageable computation speeds for the GIS-based models, it was decided that the analysis should be conducted at the 100-meter by 100-meter grid cell scale. The CDF-FRAP Multi-source land-cover map that was used as the base for vegetation and vegetation attribute mapping was created with the same resolution. Although the map was produced in 2002 and was updated following local reviewers' comments in 2003, the majority of the data used to create it came from the LCMMP (FRAP's Land Cover Mapping and Monitoring Program), which gathered data from mid-1990s Landsat satellite imagery. Nevertheless, the map is the most up-to-date land-cover data available for the state of California.

The steps needed for estimating the carbon supply for afforesting rangelands are as follows (also see **Figure 2-2**):

- Estimate the area for each change in rangeland by potential forest type;
- Estimate the quantities of carbon per unit area that could be sequestered for the change in rangeland use over a given time period;
- Estimate the total costs (opportunity, conversion, maintenance, and measurement and monitoring);

- Combine the estimated quantities of carbon per unit area with the corresponding area and cost to produce estimates of the total quantity of carbon that can be sequestered for given range of costs, in \$/ton C or \$/ton CO_2.

The carbon supply is estimated for three time durations: 20 years, 40 years, and 80 years to reflect the impact of activity duration on the likely supply and to provide an assessment for the near–term and longer-term planning horizons.

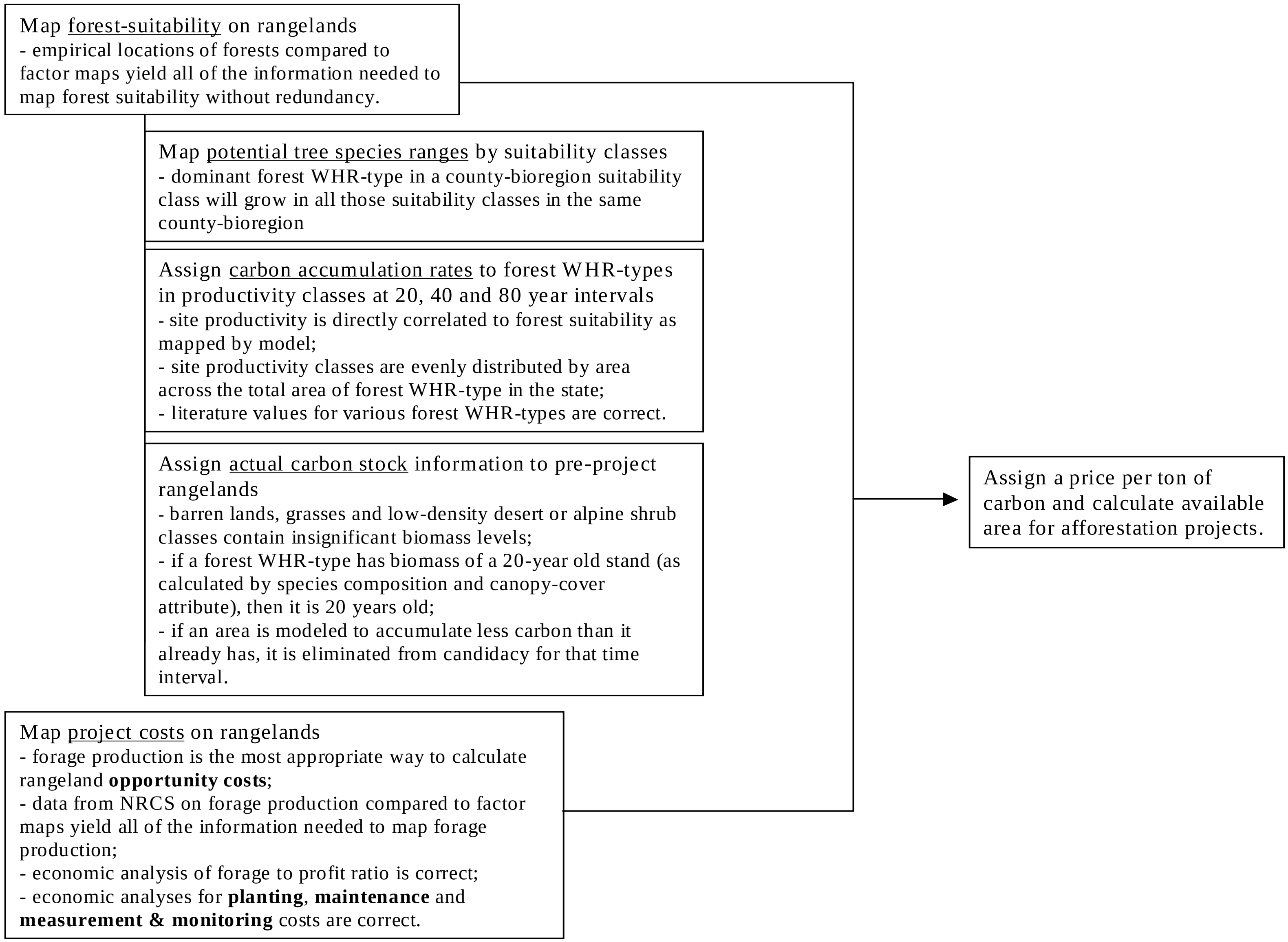

Figure 2-2. Flowchart of carbon supply curve analysis with key assumptions listed below each step.

2.3.2. Scale of Analyses

The present study aims to estimate the approximate amount of carbon that can be sequestered on the selected areas through forestry activity. The GIS datasets that cover the entire 100 million-acre area of the state are usually of a resolution coarse enough so that conventional desktop computers can display them. Working at the 30-meter grid cell resolution, which is the preferred resolution of the USGS National Land-Cover Dataset (NLCD), demands that the state be broken into two large image files of approximately 100 megabytes each. It was decided that the level of resolution of our analysis would be the same as that used by the California Department of Forestry's Fire and Range Assessment Program (FRAP) in their multi-source land cover map product: 100-meter x 100-meter grid cells. This analysis often demanded that the computer repeatedly compare over 96 million of these grid cells in the associated datasets. In addition to the complex raster processing, querying of large databases was often necessary as was reclassification of rasters based on these queries. For this analysis a Dell Precision 530 desktop computer with a 2.40 GHz processor and 2 GB of RAM was used and single operations sometimes took several minutes using macros written in the Visual Basic for Applications (VBA) programming language.

The datasets used in this analysis were coarse by NLCD standards but still often occupied the same amount of drive space as both halves of the California NLCD (**Table 2-1**).

Table 2-1. Scales and resolutions of the datasets used by the models.

Data	Resolution / Scale
FRAP Multi-source land cover map	100m x 100m
Soil Available Water Capacity to 250cm	1:250,000
Mean Annual Temperature map	1km x 1km
Precipitation	1:1,000,000
Slopes map	100m x 100m (mosaic of 30m x 30m tiles)
Elevation map	100m x 100m (mosaic of 30m x 30m tiles)

2.3.3. Definition and Area of Rangelands

The area of existing rangelands was determined using the California Department of Forestry's Fire and Resource Assessment Program's (CDF-FRAP) multi-source land-cover map (CDF-FRAP 2002). Area breakdowns for any land-cover class in California will always be subject to scrutiny due to the subtle variations in definition of the various classifications and ownership categories surveyed by different agencies with different missions. Even when using the same classification scheme, reports on general areas for California rangelands still vary.

The UC-Davis Rangeland Studies Department bases its area reports on the reclassification of the California GAP Analysis GIS land-cover products. The total area reported is higher than totals derived from the CDF-FRAP GIS land-cover products. The CDF-FRAP data indicate approximately 56.3 million acres (22.88 million hectares) of rangelands. The UC-Davis Rangeland Studies Department reports approximately 62.9 million acres although independent Winrock analysis of the GAP data yielded an estimate of approximately 55.7 million acres.

This discrepancy in area is of no surprise considering the wide variety of reporting methods and the difficulty in ascertaining exactly what criteria are used. A detailed study of agricultural and range lands in California (and their areal extents) was conducted by Kuminoff et al. (2001). The study was based on adjustments to the USDA's National Agricultural Statistics Service's (NASS) agricultural census using California Department of Conservation mapping data and adjusting for ownership categories not always mapped or sampled by NASS. The Kuminoff et al. report estimates actual rangeland area to be approximately 31.5 million acres.

Due to this seemingly inevitable variation in area reports in California, a GIS-based approach with a uniform and standardized classification methodology seems to be the best way to account for these discrepancies based on ownership restrictions in sampling techniques and the limited number of extension workers in each institution that are tasked to inventory such large expanses of land (Brown and Dushku 2002).

The critical piece of information that served as the basis of classification of all forested and rangeland landscapes was the classification scheme devised through consultation with researchers at the University of California at Davis Rangeland Studies Department (**Table 2-2**) (M. George 2003, Agronomy & Range Science Department, University of California-Davis, pers. comm.). The classification scheme in **Table 2-2** was developed to reclassify the Wildlife Habitat Relationship classification (WHR) system that is used by the CDF-FRAP to classify its land-cover maps of California and by the California Department of Fish and Game (**Figures 2-3 and 2- 4**) (Mayer and Laudenslayer 1988). The CDF-FRAP also recognizes the UC-Davis rangelands classification system (M. Rosenberg 2003, California Department of Forestry and Fire Protection, pers. comm.).

Table 2-2. The WHR rangelands reclassification system developed in consultation with University of California-Davis, California Rangelands Research and Information Center (CRRIC).

Wildlife Habitat Relationships Land-cover Type	RECLASSIFICATION
Aspen	FOREST
Closed-Cone Pine-Cypress	FOREST
Douglas-Fir	FOREST
Eastside Pine	FOREST
Eucalyptus	FOREST
Jeffrey Pine	FOREST
Klamath Mixed Conifer	FOREST
Lodgepole Pine	FOREST
Montane Hardwood	FOREST
Montane Hardwood-Conifer	FOREST
Montane Riparian	FOREST
Palm Oasis	FOREST
Ponderosa Pine	FOREST
Red Fir	FOREST
Redwood	FOREST

Table 2-2. continued

Wildlife Habitat Relationships Land-cover Type	RECLASSIFICATION
Sierran Mixed Conifer	FOREST
Subalpine Conifer	FOREST
Unknown Conifer Type	FOREST
White Fir	FOREST
Agriculture	NEITHER
Barren	NEITHER
Estuarine	NEITHER
Freshwater Emergent Wetland	NEITHER
Lacustrine	NEITHER
Marine	NEITHER
Riverine	NEITHER
Saline Emergent Wetland	NEITHER
Urban	NEITHER
Water	NEITHER
Alkali Desert Scrub	RANGE
Alpine-Dwarf Shrub	RANGE
Annual Grassland	RANGE
Bitterbrush	RANGE
Blue Oak Woodland	RANGE
Blue Oak-Foothill Pine	RANGE
Chamise-Redshank Chaparral	RANGE
Coastal Oak Woodland	RANGE
Coastal Scrub	RANGE
Desert Riparian	RANGE
Desert Scrub	RANGE
Desert Succulent Shrub	RANGE
Desert Wash	RANGE
Joshua Tree	RANGE
Juniper	RANGE
Low Sage	RANGE
Mixed Chaparral	RANGE
Montane Chaparral	RANGE
Pasture	RANGE
Perennial Grassland	RANGE
Pinyon-Juniper	RANGE
Unknown Shrub Type	RANGE
Sagebrush	RANGE
Valley Foothill Riparian	RANGE
Valley Oak Woodland	RANGE
Wet Meadow	RANGE

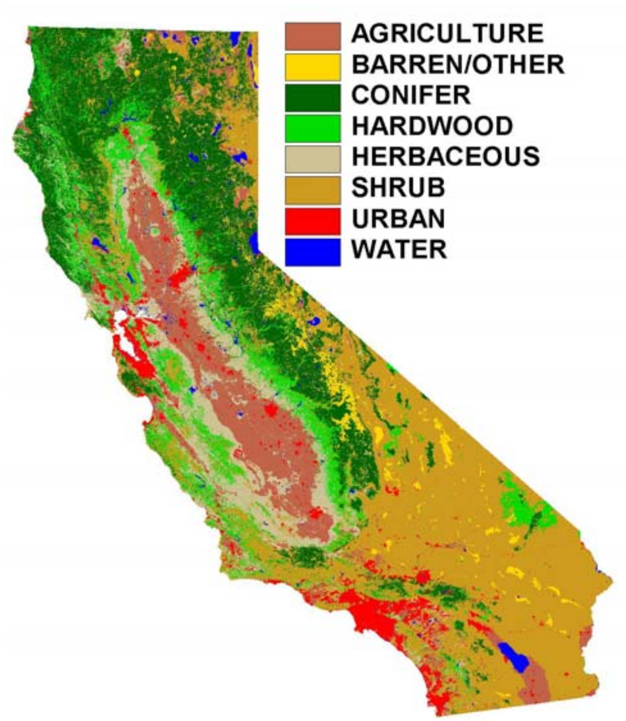

Figure 2-3. CDF-FRAP multi-source land-cover map classified into major land cover types (more than 77 WHR classes are actually present in the map).

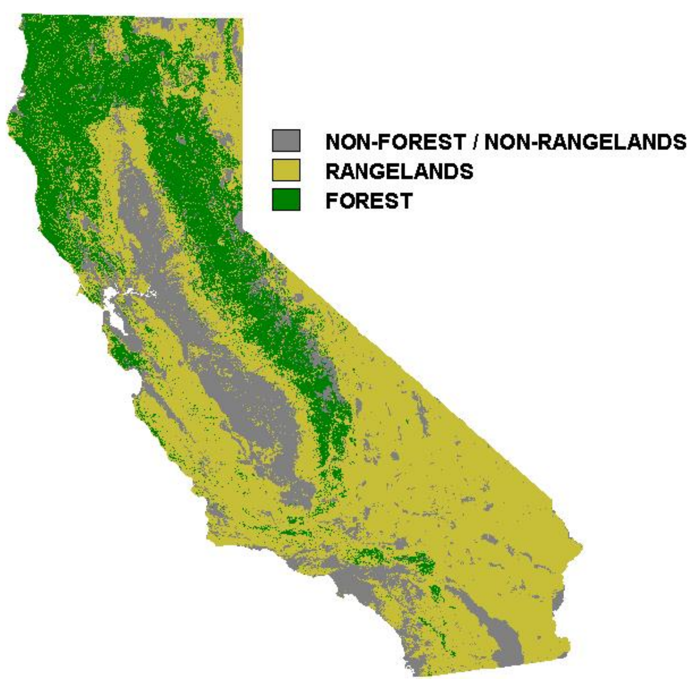

Figure 2-4. Reclassification of multi-source land-cover map.

2.3.4. Identification of Rangeland Suitable for Afforestation

2.3.4.1. Determining forest suitability

In the first step of the analysis, the goal is to identify which existing rangelands could potentially be afforested. To accomplish this task, the map of California's rangelands was cross-referenced to suitability maps for forest land-cover. The suitability for forests is based on the wood productivity index of state STATSGO databases (woodprod) (Schwarz and Alexander 1995). For California, the woodprod for the dominant soil components across the STATSGO soil-type polygons accounted for only 9% of the state, thus a method was developed to extrapolate to the rest of the state.

To extrapolate the woodprod index to the rest of the state, a simple multivariate regression approach using precipitation, soil available water capacity, mean annual temperature, slopes and elevation was tried. The results from this effort produced such a low r^2 that it was decided that this was not the approach to use. Instead, a model was developed that combined several different biophysical factor maps to produce a suitability map for forest growth calibrated using empirical locations of actual forests (**Figure 2-5**) using the same factors as above.

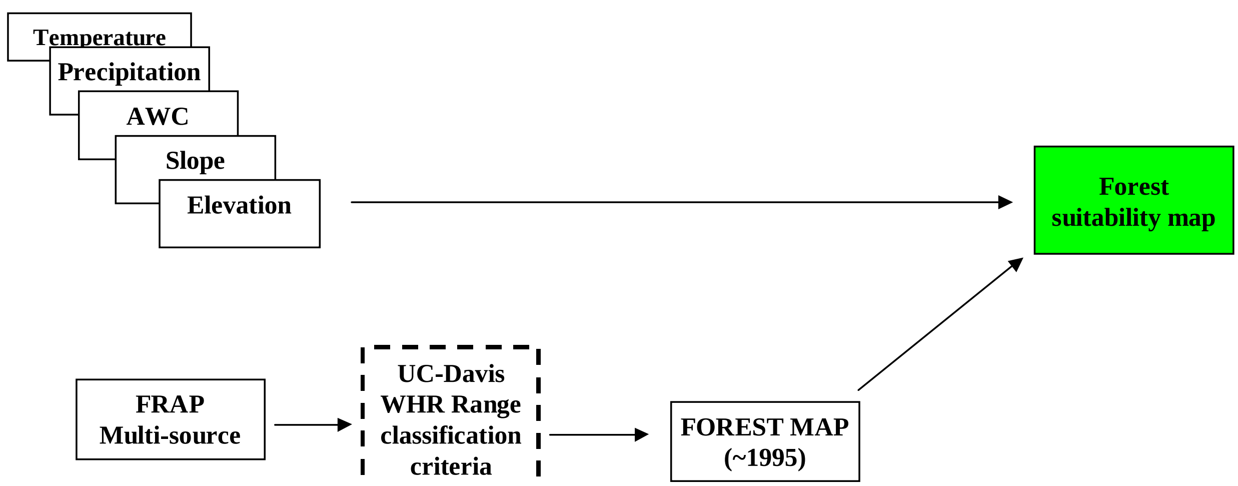

Figure 2-5. Steps used to develop a suitability map for converting existing rangelands to forests. (AWC = Available Water Capacity of soil)

To map forest suitability, quantitative factor maps (**Appendix B**) are used to gauge biophysical properties of the landscape which favor forest growth (**Table 2-3**). The model uses a factor set similar to the set that others have used to model net primary productivity by land-cover types (Wang et al. 2002; Mickler et al. 2002). The factors elevation, mean annual precipitation and temperature are commonly used variables for creation of general plant distribution and habitat maps (Küchler 1964; Bailey et al. 1994; Lugo et al. 1999). Development of the modeling methodology was also based on lessons learned from a pilot study with similar goals in the states of Mississippi, Arkansas and Louisiana (Winrock International 2003) and industry standard methodologies for suitability mapping with GIS (Eastman 2003, Wayne 2003a & 2003b).

Table 2-3. Factor maps used. See Appendix C for the dataset descriptions.

Data	Source
Soil Available Water Capacity to 250cm	Miller et al. (1998)
Mean Annual Temperature map	Thornton et al. (1997)
Precipitation	CASIL (2004)
Slopes map	CASIL (2004)
Elevation map	CASIL (2004)

(CASIL is the California Spatial Information Library – http://gis.ca.gov/)

These statewide factor maps are divided into categories. These categories are ranges in their values grouped at equal intervals (e.g., two elevation categories of 0-100 and 100-200 feet above sea level, respectively). For each factor map, the model extracts empirical information on the proportion of the number of forested grid cells within each of these categories (**Figures 2-6 through 2-10**). This proportion information is used to weight each category in each factor map for forest suitability. The weights are then substituted for the old values of the categories (i.e., "proportion of forest in category" replaces "feet above sea level" range) creating probability maps based on each factor. Then all grid cells in the factor maps, with these new weights as their values, are averaged across maps to create one map with a general suitability value in each cell. This methodology uses analysis modules featured within the Idrisi Kilimanjaro GIS and remote sensing software package that were first developed by Hall el al. (1995) and Pontius et al. (2001).

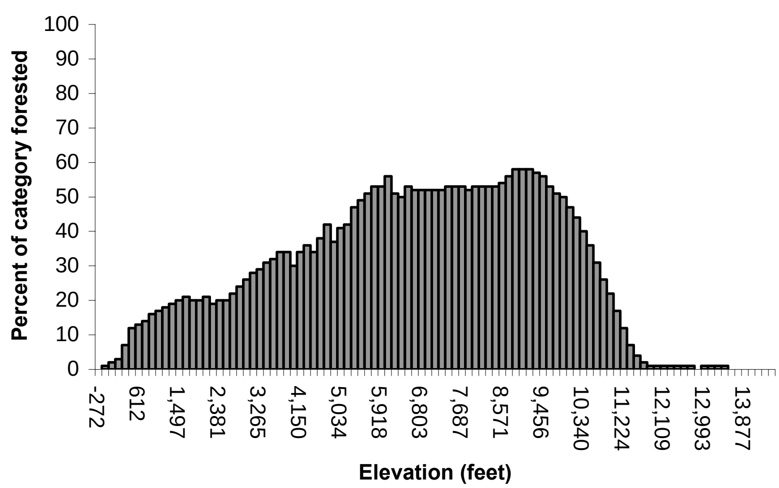

Figure 2-6. Proportion of actual forest in each of the Elevation map classes. Units are feet above sea level.

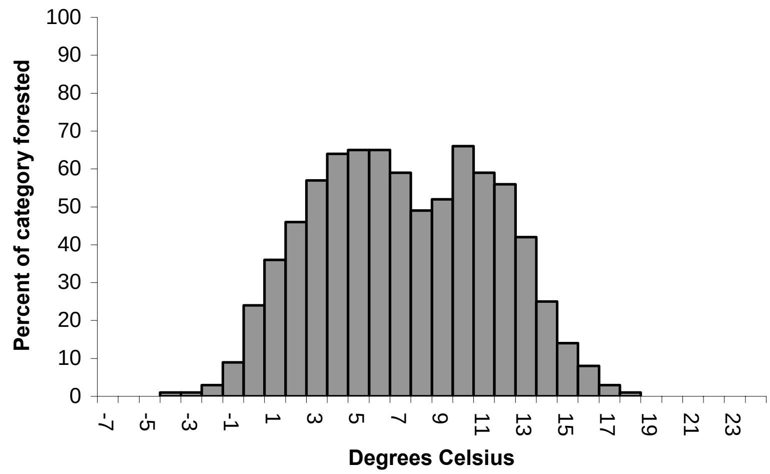

Figure 2-7. Proportion of actual forest in each of Mean Annual Temperature map classes.

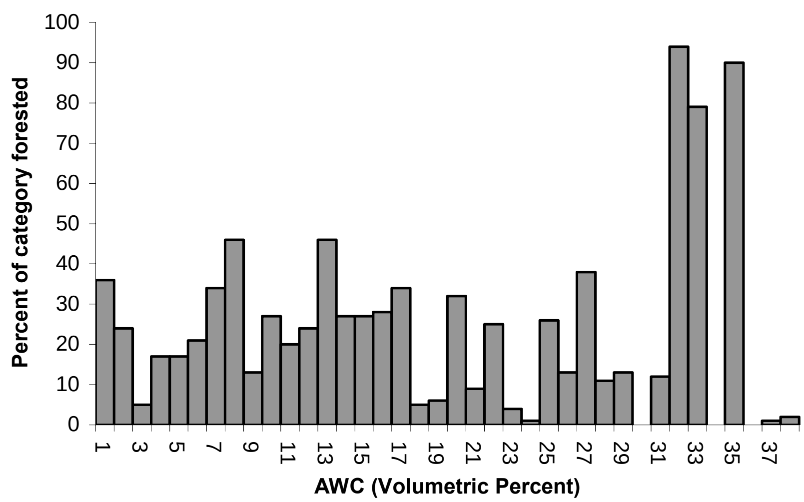

Figure 2-8. Proportion of actual forest in each of Soil Available Water Capacity map classes.

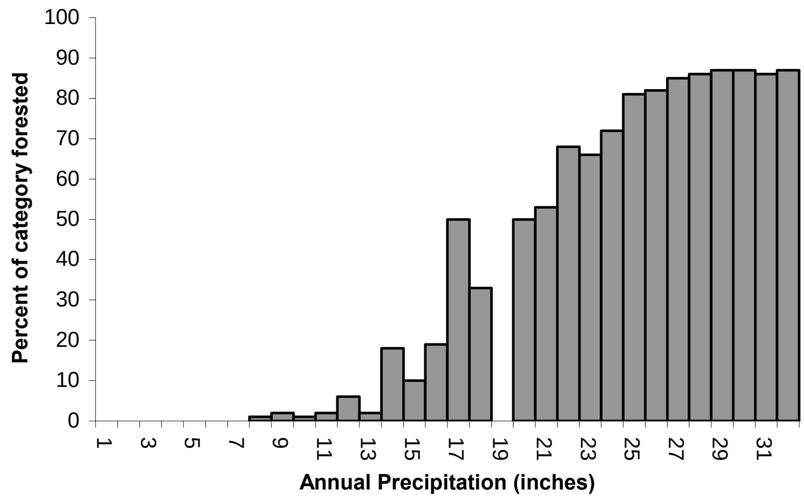

Figure 2-9. Proportion of actual forest in each of Precipitation map classes.

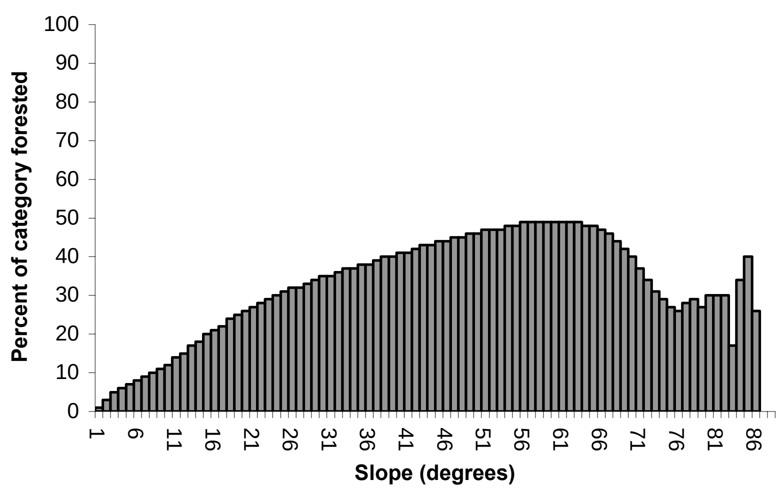

Figure 2-10. Proportion of actual forest in each of Slope map classes.

The model is empirically driven based on the distribution of forestlands within the factor map classes. Because of this, some factor maps may be cross-correlated (i.e., elevation and precipitation) and no statistical analysis was conducted to quantify this. One of the strengths of the model is that it was created in a way in which policy-makers and stakeholders at both the national and local level can understand it and replicate it if necessary. In keeping with this goal, some assumptions are made as presented in **Figure 2-2**. The scope of this study is to produce statewide estimates and the results of this study are based on a model with input datasets that are mapped at a 100m x 100m grid cell resolution. Therefore, before engaging in any afforestation activity at the local level, it is recommended that these analyses be repeated at the finer scale with careful attention to the selected sites' behavior with respect to the individual factors as seen in **Figures 2-6 through 2-10**. In some cases, when the majority of the factors apparently indicate the suitability of a site to grow forest species, yet, it is known that at there are rigid constraints to forest growth in a range of values in one key factor map, a more detailed look at the site could be merited. This might include careful examination of this specific factor at the given site. However, for the most part, because the model is empirically driven and because it averages the values of all the factor maps, this type of situation is rare. To be classed among the most suitable sites, a location needs to have high values across all the factor maps.

The general suitability map for forests that was produced by the model is shown in **Figure 2-11**.

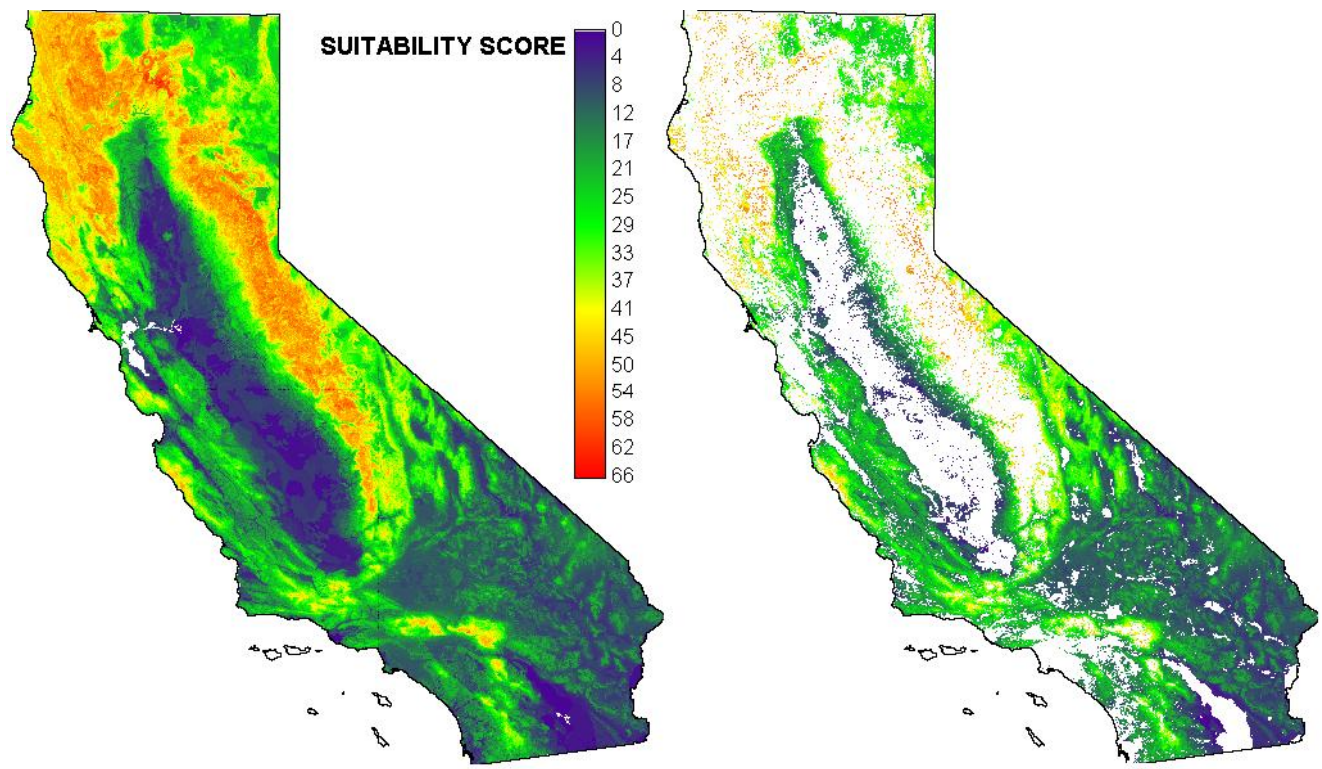

Figure 2-11. All areas "suitability" for forest growth (left) and rangeland areas "suitability" for forest growth (right) according to the model. Low score means unsuitable for forests, and the higher the score the more suitable for forest growth.

The reclassified land-cover map was then compared to the suitability map to show the current range and forest distributions within its different suitability classes (**Figure 2-12**). This allows us to see ranges within the suitability scale where forests and rangelands currently exist and where potential transformation of rangelands to forests should be explored.

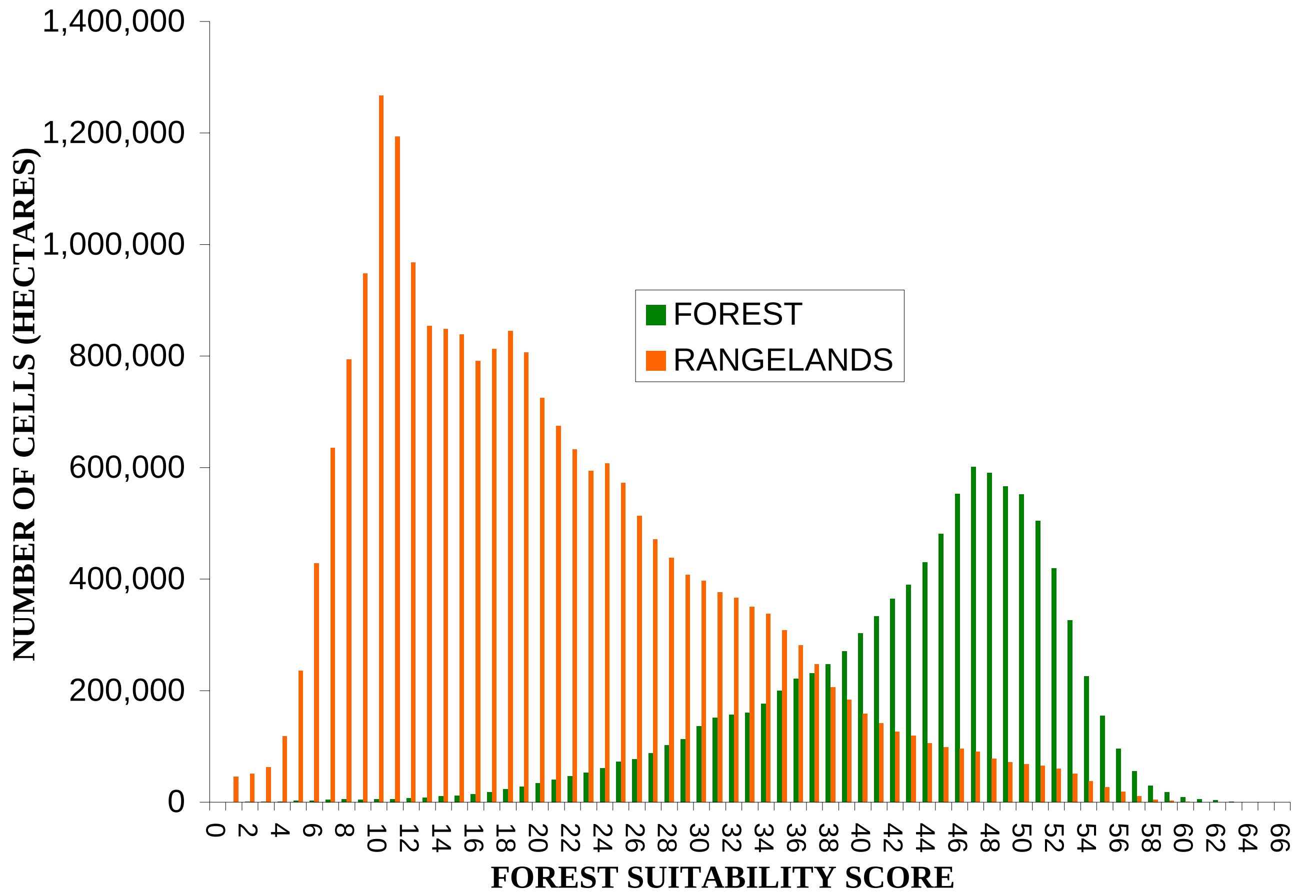

Figure 2-12. Distributions of areas of current range and forest in forest suitability classes.

From an approximate suitability score of 20 and higher, there is an overlap of forest classes in areas that exhibit the same biophysical characteristics as current rangelands (**Figure 2-12)**. There are approximately 23.6 million ac or, 9.3 million ha, of current rangelands with a forest suitability score greater than 20. We assume, therefore, that rangelands with a suitability score of 20 or greater are suitable for forest growth. It is within these areas that we will further explore the potential for carbon sequestration and the costs. It is also possible to see what proportions of some more specific land-cover types currently exist in the different forest suitability map classes by comparing maps of generalized WHR-classes to the suitability map (**Figures 2-13 through 2-15**).

When all of the WHR classes in California are aggregated into three classes of "forest," "rangelands," and "non-forest and non-rangelands," the distribution of the land in these classes within the mapped forest suitability classes can be examined (**Figure 2-13**).

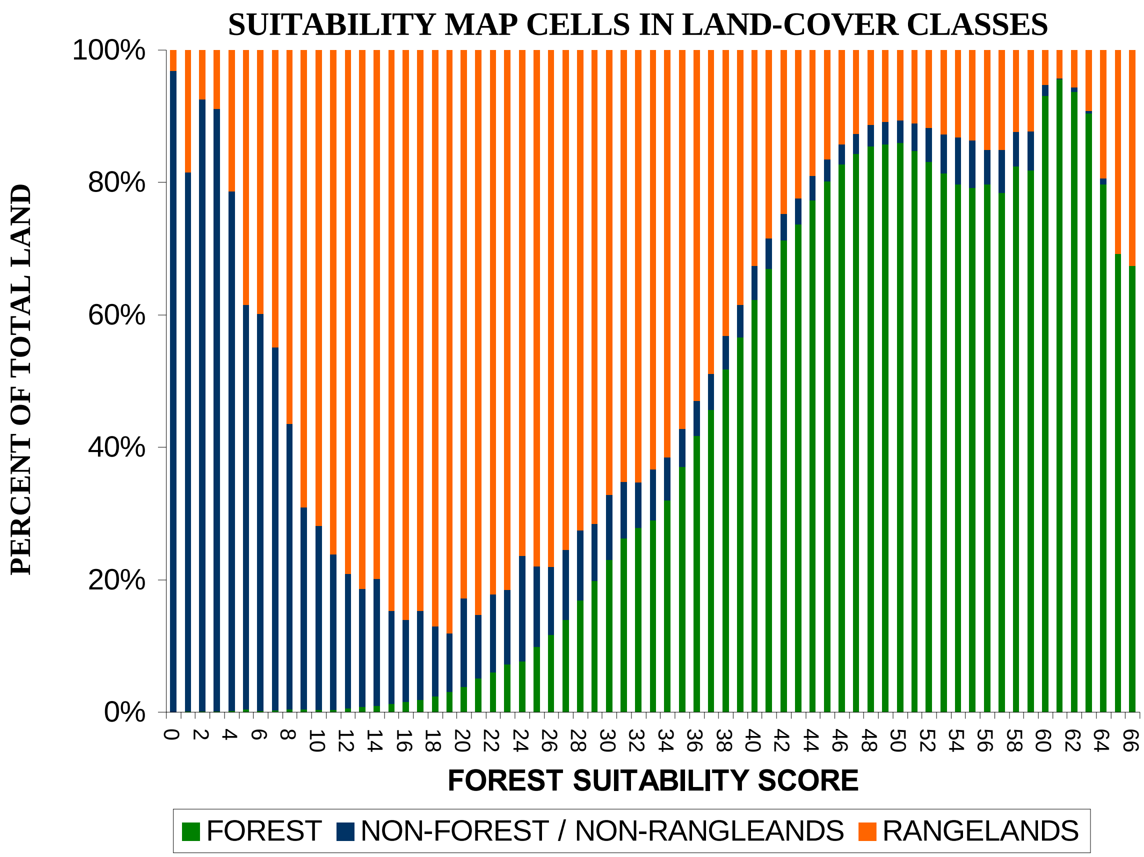

Figure 2-13. Distribution of 3 WHR generalized classes within the forest suitability classes. (This is the intersection of Figures 2-4 and 2-11).

From **Figure 2-13** it is apparent that the distribution of forest WHR-types are in the highest suitability classes. However, some rangeland WHR classes are present in the higher forest suitability classes and notably so, above suitability score 20.

When further resolution is added to the WHR-classes (**Figure 2-14**), it can be seen that the higher forest suitability classes currently contain mostly conifer and hardwood forests but also, some shrubs.

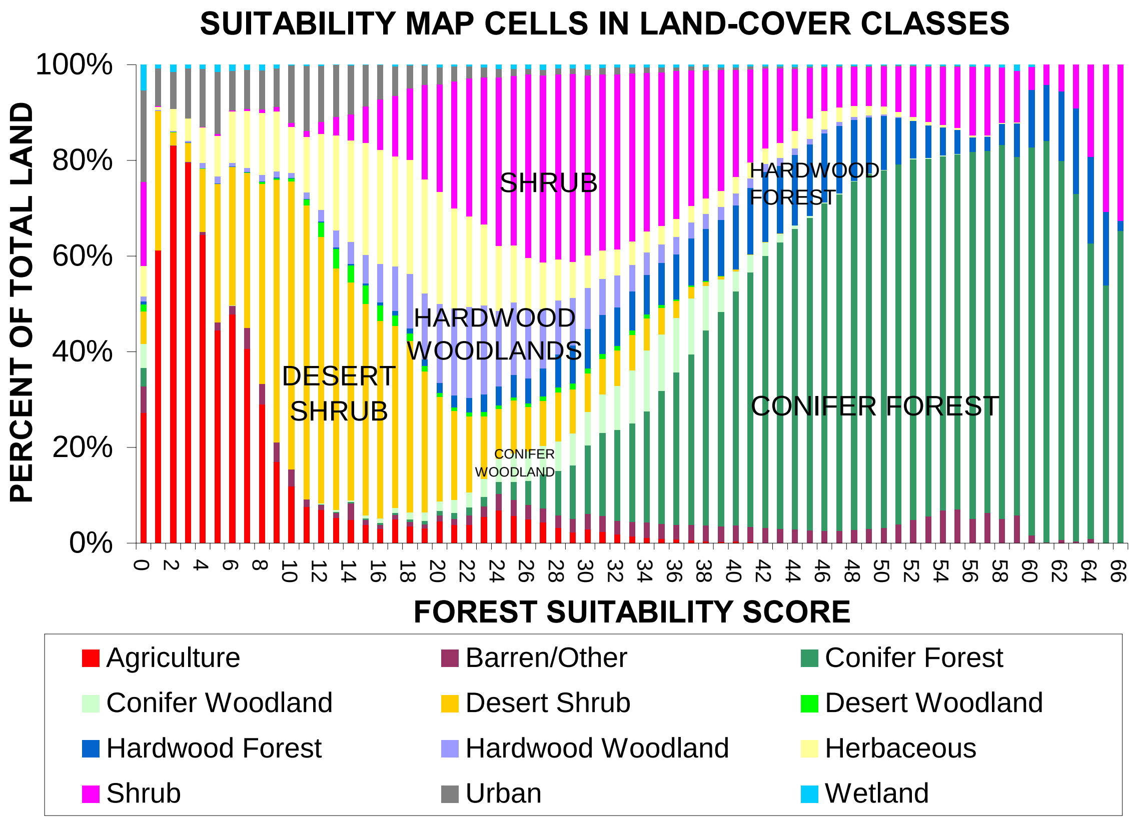

Figure 2-14. Distribution of 12 WHR generalized classes within the forest suitability classes.

Other generalized classes found in areas above forest suitability score 20 include hardwood woodlands, desert shrub, herbaceous lands and conifer woodlands. Desert woodlands, agriculture, urban and barren areas are also all present in traces above 20.

Next, we examine the current rangeland WHR-types only that exist in the different suitability classes (**Figure 2-15**).

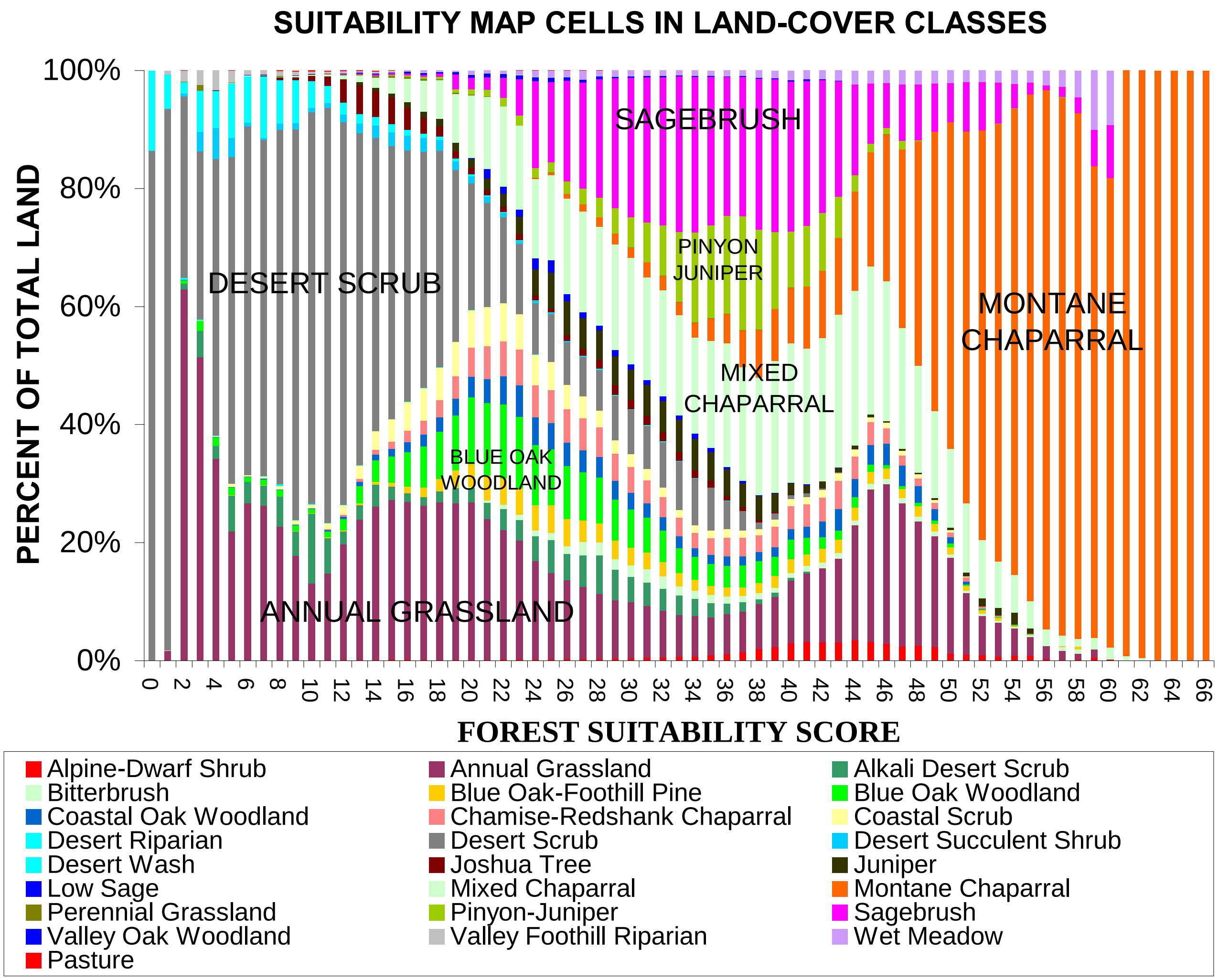

Figure 2-15. Distribution of rangeland WHR classes within the forest suitability classes.

Apparently, the dominant existing WHR-type in the highest classes of forest suitability is montane chaparral. Some mixed chaparral, annual grassland and sagebrush also exist in those higher classes of forest suitability while oak woodlands gradually make their appearance as well. To support the assumption that forests could grow and perhaps that forests once grew on many areas of montane chaparral, all montane chaparral candidate cells were mapped with the populated places layer from the California Spatial Information Library on top of them. Many of the names of the populated places included logging references like "Mill" or "Camp" and, also, tree species names like "Pines," "Oaks," or "Cedars" (**Figure 2-16**).

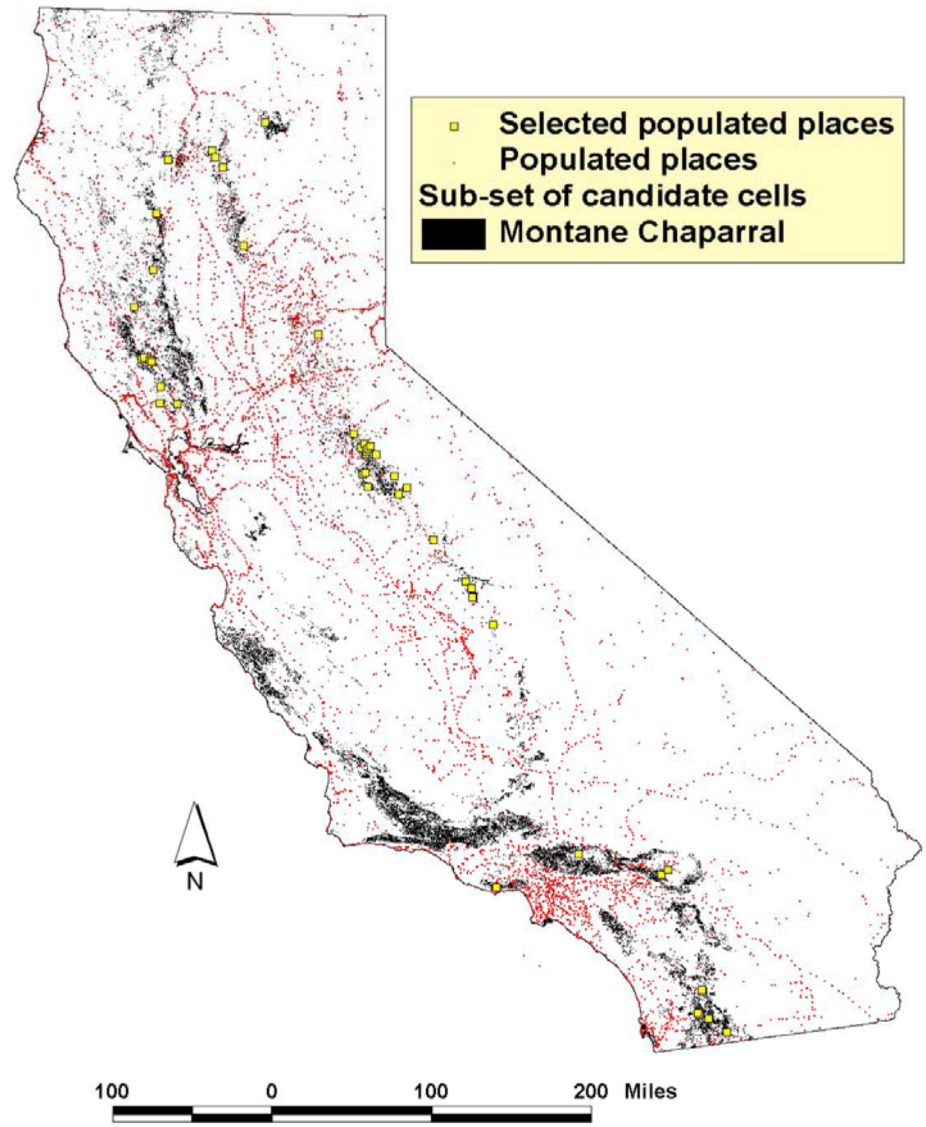

Figure 2-16. Map of populated places (dots), Montane Chaparral areas, and selected place names with reference to forests or forestry (squares).

Populated place names include: Alder Springs, Angelus Oaks, Big Oak Flat, Black Oaks, Caldwell Pines, Camp Earnest, Cascadel Woods, Cedar Ridge, Cedar Springs, Cedarbrook, Coulterville, Crabtree, Deadwood, Fall River Mills, Forest Lake, Forest Ranch, Foresta, Furnaceville (historical), Goodmill, Groveland, Hathaway Pines, Hess Mill, Howard Mill (historical), Hughes Mill, Hulburd Grove, Kentwood-In-The-Pines, Live Oak Springs, Oak Bottom (historical), Oak Grove, Oak Hill, Oak Run, Oakmont, Oakville, Pine Grove, Pine Valley, Pinehurst, Redwoods, Sequoia, Seven Oaks, Sherwood Forest, Skinner Mill Place, Stallion Oaks, Sugarpine, Tall Timber Camp, Whispering Pines, and Woodleaf.

The suitability score produced by the model and charted on the x-axis of **Figure 2-15** is a derived index of forest growth potential. This score was derived by using a combination of the selected factors and the distribution of forested lands within them. Later on, the score will be used to estimate biomass accumulation over time and costs will be analyzed for potential afforestation activities based on those rates and associated other costs.

2.3.4.2. Determining potential woody species to plant on suitable sites

To determine the carbon sequestration potential on rangelands with a suitability score of >20, it is necessary to examine the forest species that could potentially be planted. To find out which species could grow successfully in rangeland areas that were determined to be suitable for forest growth, a number of analyses were conducted. Because different WHR-types could dominate a suitability class in different parts of the state, the state was broken down into counties and the counties were broken down into biologically distinct regions. These bioregions were identified by the California Biodiversity Council (CBC) and mapped by CDF-FRAP (2003) (**Figure 2-17**). For each suitability class, in each of these areas (county-bioregions), the woody WHR class with the greatest dominance was selected as the potential species for planting (**Figure 2-18**).

Figure 2-17. California Biodiversity Council (CBC) Bioregions map (DCF-FRAP, 2003). Inset box shown in Figure 2-18.

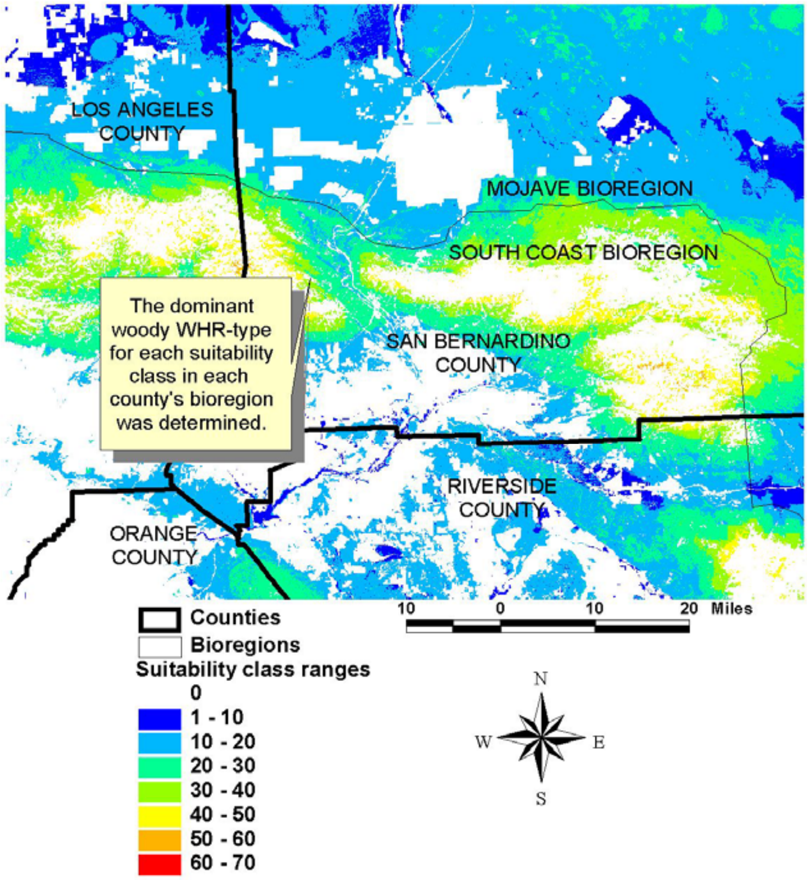

Figure 2-18. An example of the stratification of the suitability map by county and bioregion in an area of southern California. For each suitability class in each county's bioregion, a woody WHR-type was assigned based on its dominance in area in the class.

Woody WHR classes not only include forest classes but also some rangeland classes that contain high levels of woody biomass. These woody WHR classes include all those listed as forest in **Table 2-2** plus, the woodlands listed as valley foothill riparian, blue oak woodland, blue oak-foothill pine, coastal oak woodland and valley oak woodland. Additional consideration was given for a desert woodland category that included non-forest species such as desert riparian, pinyon-juniper and juniper. Should an area already classified as one of these rangeland species be again selected by the model as an area suitable for more of the same species, then changes in management should allow for an increase in canopy cover and consequently, an increase in biomass. Candidate areas are those areas that are either non-woody rangelands or woody rangelands with a canopy cover of less than 40% that exhibit a suitability score greater than 20. Canopy density of the various land-cover classes is determined by CDF-FRAP through remote sensing analyses and field reconnaissance and is provided as part of their multi-source land-cover product's geodatabase (CDF-FRAP 2003). Density ranged from "S" to "D" and the definitions of these classes are listed in **Table 2-4**.

Table 2-4. WHR density classes and associated tree or shrub canopy closure definitions.

Tree Canopy	Description (% Canopy Closure)
S	10 to 24%
P	25 to 39%
M	40 to 59%
D	60 to 100%
	Not Determined

Source: CDF-FRAP

In some cases woody rangelands are mapped with a canopy density of more than 40%; we assume that these ecosystems are in a natural state and are not considered as potential areas for reforestation. Thus, woodlands with canopy closures over 40%, existing forestlands, agriculture, urban areas and aquatic ecosystems have all been removed and the areas of these candidate cells are shown in **Figures 2-19 and 2-20**.

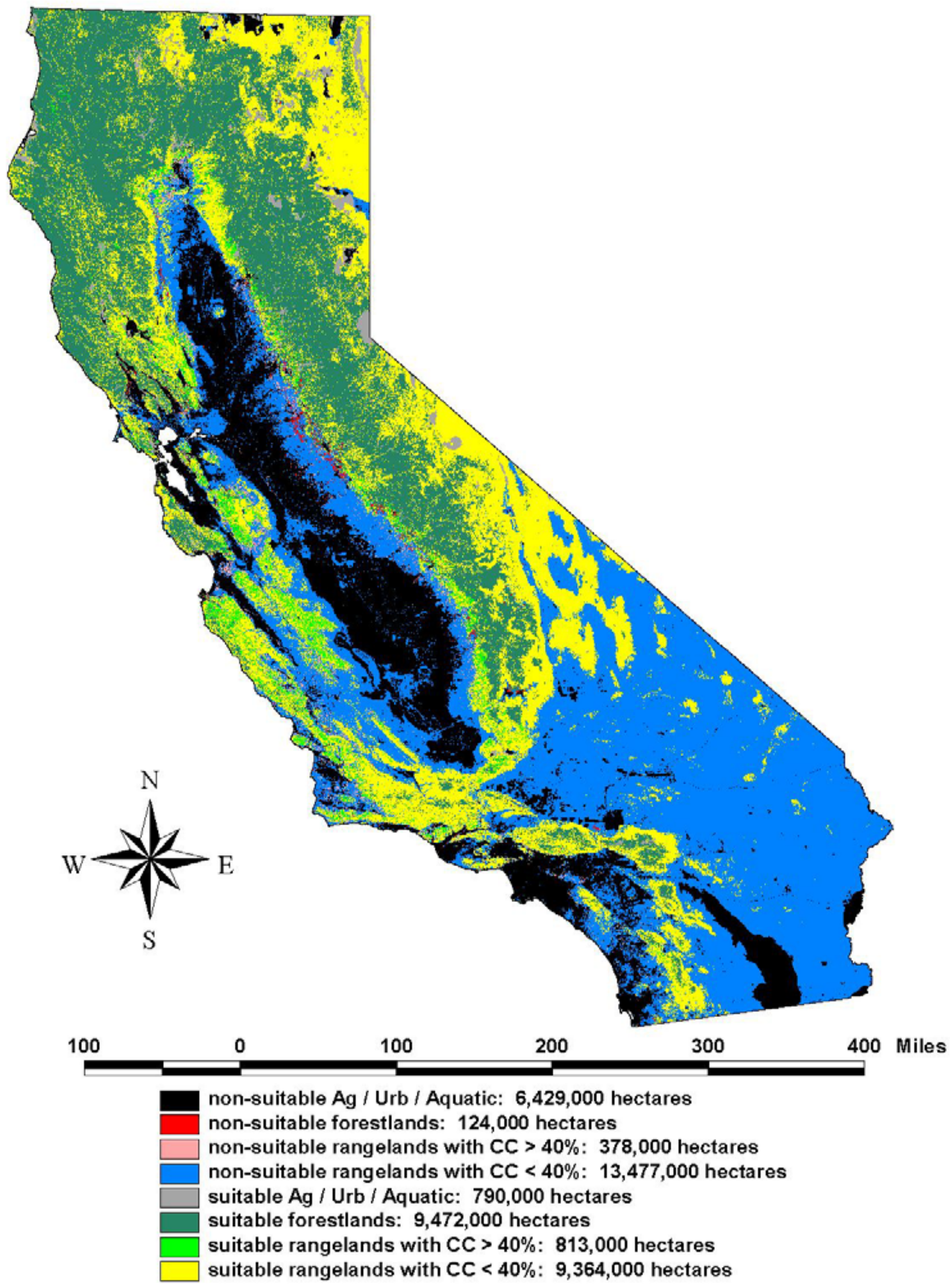

Figure 2-19. Map of candidate areas, i.e., those areas of rangelands with a canopy coverage of less than 40% and that scored higher than 20 on the suitability map.

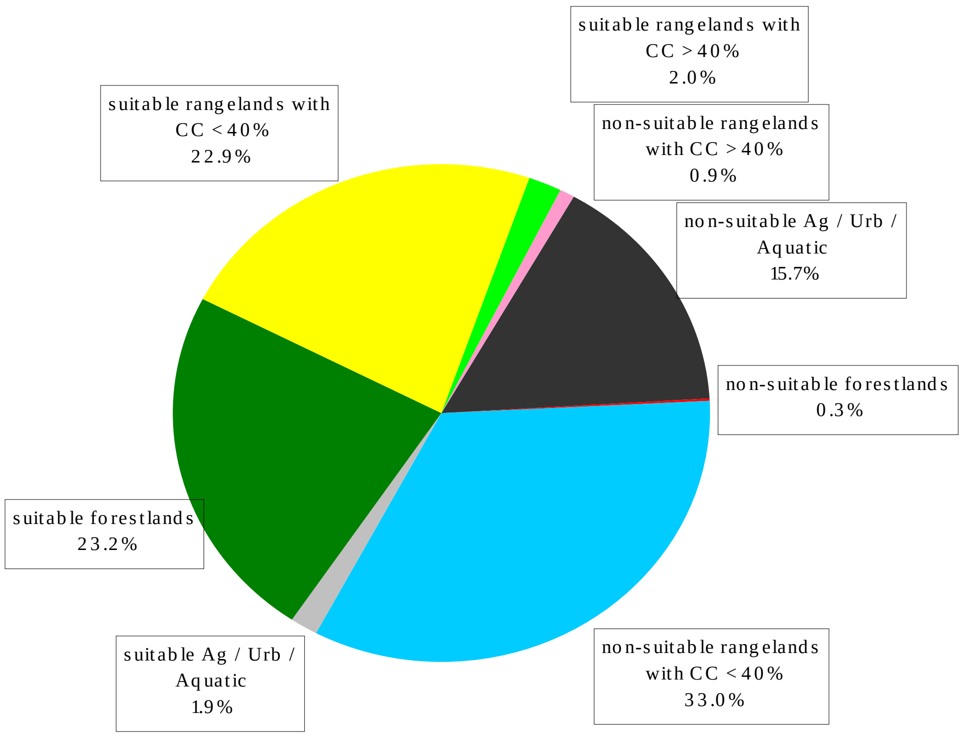

Figure 2-20. The breakdown of the candidate cells in California. Candidates for carbon sequestration activity through forestry ("suitable rangelands with CC<40%--about 23% of California or 9.4 million hectares). "Suitable" areas are those that scored higher than 20 on the suitability map. (CC=canopy cover).

2.3.4.3. Predicting forest carbon sequestration potential

Existing models of forest growth were considered, including CRYPTOS and CACTOS models developed at U.C. Berkeley (Wensel et al. 1982; Meerschaert et al. 1987) and Forest Vegetation Simulator developed by the U.S. Forest Service. These models project growth and mortality at an individual tree level and require input of existing (initial) forest inventory data as well as an array of site-specific conditions, and consequently were deemed to be less useful for application to the large scale of this effort. Therefore, models were developed to directly estimate rates of forest carbon accumulation on a per unit area basis, and that would require a manageable suite of inputs: WHR class and Forest Suitability class. To simplify, other factors influencing forest growth (e.g., site preparation, planting density, management) were held constant.

Carbon sequestration potential for all WHR classes coinciding with Forest Suitability scores >20 were estimated from the forest inventory and analysis database (FIADB) for California and the USFS Silvics of North America (Burns and Honkala 1990) as well as Lloyd et al. (1986). Reported volumes for mature stands (here chosen to represent the asymptote of the growth curve) were converted to above- and below-ground biomass using the formulae of Smith et al.

(2003) and Cairns et al. (1997). As well, where a single WHR class had significant coverage across a wide range of Forest Suitability classes (>10 classes), the WHR class was further broken down into three forest productivity classes (high, medium, and low productivity), again referencing values reported in the FIADB for California and the USFS Silvics of North America (Burns and Honkala 1990). The medium productivity class for each forest type was centered on the Forest Suitability class that had the greatest area of forest coverage (the mode), and extended one-third of the distance to the extreme high and extreme low Forest Suitability class values registered. The high and low productivity classes were then allocated to either side of the medium class.

The age at which mean annual increment (MAI) peaks, roughly the age at which stand volume begins to level off (here assumed to be the age at which yield = 80% of the asymptote) was determined in consultation with Josephson (1962), referencing empirically-derived yield tables, and the USFS Silvics of North America. Age together with yield allowed determination of one point (time:biomass/ha) along an envisioned biomass yield curve.

The Chapman-Richards function (Richards 1959; Pienaar and Turnbull 1973), a popular sigmoid-shaped biological growth model, where:

$$yield = a \times (1 - e^{(-k \times age)})^{1/(1-m)}$$

was chosen to model biomass carbon accumulation over time. Parameters for Chapman-Richards models were estimated to tailor carbon yield curves for each WHR class, and passing through the previously determined age:biomass/ha points.

- "yield" is expressed in metric tons of biomass
- "age" is expressed in years
- "a" (asymptote) determined previously
- "m" parameter set iteratively at 0.7 (fraction of asymptote (final yield) at which growth rate peaks),
- back calculation for "k" (rate at which the asymptote is approached)

Estimates of the carbon stocks generated by the model are (**Figure 2-21 and 2-22**):

- For conifers at 80 years, the range is from 60 t C/ha for lodgepole pine to 594 t C/ha for the highest productivity class of redwood,
- For hardwoods at 80 years, the range is from 46 t C/ha for low productivity oak woodland to 344 t C/ha for high productivity montane hardwoods (with some softwood component).

The high values derived for high-productivity redwood stands, up to 594 t C/ha at 80 years, are not unreasonable for what are widely recognized as the highest biomass forests in the world (Walker 1998). These high-productivity redwood stands, however, make up less than 25% of the areas mapped as suitable for redwoods and less than 1% of the total candidate cells in the analysis.

The area-weighted averages across all the candidate rangelands for carbon accumulation were, 38.9 t C/ha at 20 years, 109.9 t C/ha at 40 years and 178.1 t C/ha at 80 years.

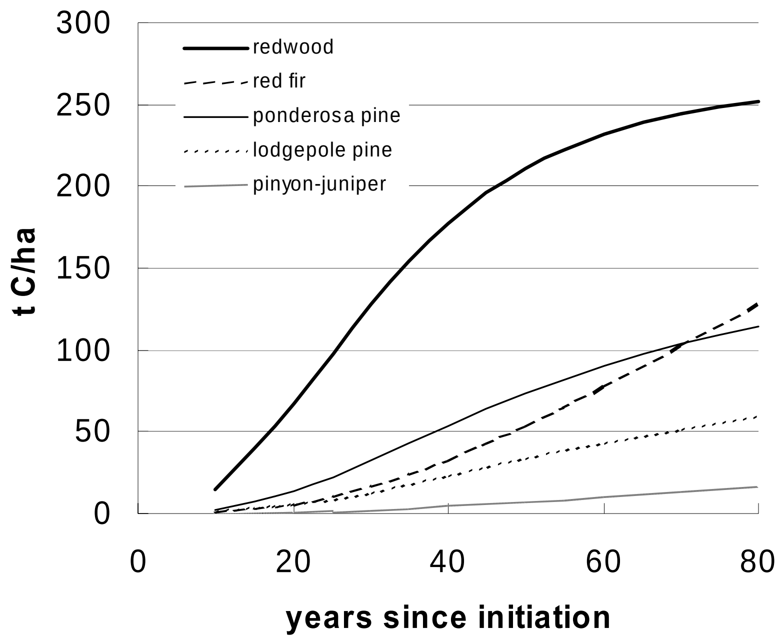

Figure 2-21. Forest biomass carbon accumulation potential for selected California conifers. Redwood curve is shown for the more common low-productivity stands.

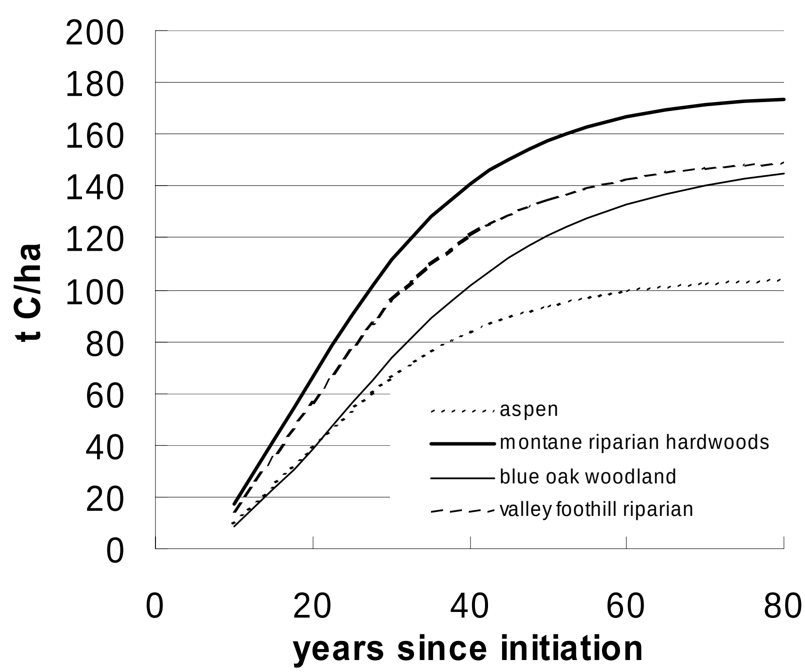

Figure 2-22. Forest biomass carbon accumulation potential for selected California hardwoods.

The existing WHR types on rangelands mapped as suitable for afforestation were each given a baseline carbon density index based on WHR-type (**Table 2-2**) and 'WHR-density' (**Table 2-4**). The area-weighted average for baseline carbon stocks on all of the candidate rangelands was approximately 13 t C/ha.

By subtracting the baseline carbon estimates from the estimated accumulation values at a given location, net carbon accumulation was mapped over 20, 40 and 80 year growth periods (**Figure 2-23**). Weighted averages for *net* carbon sequestration potential on the candidate rangelands of the state were 28.7 t C/ha after 20 years, 97.9 t C/ha after 40 years and 165.7 t C/ha after 80 years. In some cases, the model predicted carbon accumulation that was less than the estimated baseline carbon. This resulted in a negative net carbon accumulation potential in some years. For the purposes of calculating area-weighted averages of carbon accumulation potential, these areas with negative values were considered as zeros and, as a result, a slight discrepancy in the overall area across the 20, 40 and 80-year marks may be evident (**see also Section 2-4. Results**).

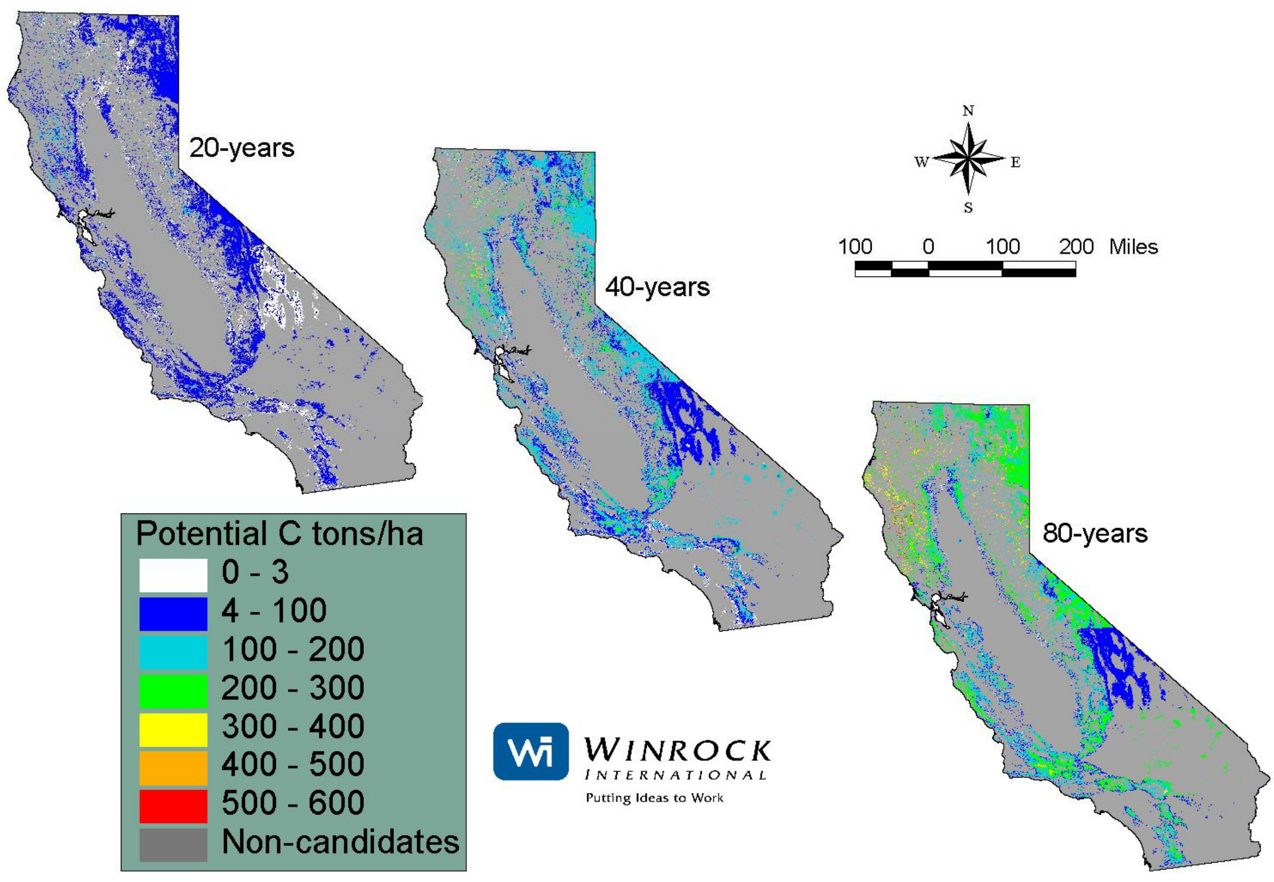

Figure 2-23. Net potential carbon accumulation curves applied to potential woody-species distributions over three potential periods.

2.3.5. Analysis of Carbon Sequestration Costs

This section describes all of the estimated costs for producing carbon through afforestation of rangeland in California. These costs are used in the construction of carbon supply curves that depict, for this class of activities, the estimated quantity of carbon supplied over a range of possible carbon prices. The categories of costs that were estimated in this analysis include:

- opportunity costs,
- planting and other conversion costs,
- measuring and monitoring (M&M) costs, and
- maintenance costs.

Each of these cost categories is described below followed by discussion of the resulting carbon supply curves in Section 2-4.

2.3.5.1. Opportunity costs

All economic decisions involve trade-offs. If activity x is forgone in order to undertake activity y, then the value of undertaking activity x must be considered as the opportunity cost of undertaking activity y. Simply put, the opportunity cost is the most highly valued alternative to the activity being considered. In this case, the activity being considered is afforestation of rangelands. The most highly valued alternative to afforestation is cattle ranching. Therefore, the profitability per hectare of cattle ranching in California represents the opportunity cost of producing carbon (i.e., afforestation).

An alternative to afforestation of rangelands could be conversion to urban development, and depending upon the price of real estate, the opportunity cost for this alternative could be high. We did not consider this alternative in our analysis. However, we do discuss this issue further (Section 2.6.2) in light of the work by Landis and Reilly (2003) on projected urban development on rangelands.

The focus on estimating opportunity cost for rangeland is for cattle ranching for beef rather than dairy. The profitability of cattle ranching varies greatly from year to year and from ranch to ranch. This is due primarily to weather conditions and cyclical fluctuations in the price of beef. Unfortunately annual enterprise budgets for cattle ranching, which indicate profitability, are not officially kept in California as they are for many other agricultural activities. Because of this, we used the input of several ranchers and rangeland extension specialists to calculate an average annual profitability value for California cattle ranching.[2] These values are designed to be long-term averages, however variability around these averages will be significant. The revenue estimates that can be seen in **Table 2-5** reflect long-term average prices received for

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2 From personal communication from the following: S. Barry 2003. Bay Area Natural Resources/Livestock Advisor. Santa Clara, Alameda, San Francisco, San Mateo and Contra Costa Counties Cooperative Extension, University of California-Davis, San Jose, California; Jim & Virginia Coelho 2003. Alameda County Ranchers, and California; D. Lile 2003, County Director/Interim Farm Advisor, Lassen County Cooperative Extension, University of California-Davis, Susanville, California.

cattle. After subtracting total costs of production from revenue, an average annual profit per cow is estimated to be $67.50.

Table 2-5. Revenue and costs associated with cattle ranching in California.

Economics of California Ranching			
Revenue			
	Total	$/cow	Assumptions
Calf	$500.00	$425.00	85% wean rate
Cull cows	$450.00	$67.50	15% cull rate
Total Revenue		**$492.50**	
Costs in $/cow			
Pasture		$111.00	(Including cost for bulls - 5% of herd)
Supplemental feed		$145.00	(Including replacement heifers - 15%)
Other operating and fixed costs		$169.00	
Total Costs		**$425.00**	
Mean Annual Profit per Cow (Revenue – Costs)		**$67.50**	

Other than the wide swings in the price received for cattle, the most critical variable in determining ranching profitability is the forage production potential of the rangeland. Forage production determines the carrying capacity of the land. Higher forage production can support more cows per acre and therefore results in higher profits per acre. Moisture and soil conditions are the primary predictors of rangeland productivity and are the drivers of the methodology described below.

California rangeland specialists use an average of 791 lbs. of forage dry matter (DM) to represent the monthly requirements for cattle being fed on rangeland forages (L. Metz 2003, USDA-NRCS, Davis, California, pers. comm.). This monthly requirement is termed an animal unit month (AUM) and it is used as a measure of the carrying capacity of a parcel of rangeland. Therefore, if one acre of rangeland produces 791 lbs. of forage DM over the course of one month, that acre is said to produce one AUM of forage. This translates into an annual per cow forage requirement of 9,492 lbs. DM (12 times the AUM). We have used this forage requirement estimate (i.e., AUM of 791 lbs.) and the average annual per cow profitability of $67.50 to estimate the profitability potential (i.e., opportunity cost) for all California rangelands, as explained in the following paragraph.

The forage production of any given acre of rangeland determines its carrying capacity. The carrying capacity determines the profit that can be made from that acre. For example, rangeland that only produces 100 lbs. of forage DM per acre will require almost 95 acres to support one head of cattle for a year. The annual per acre profitability of this low-producing rangeland is estimated to be only \$0.71 (i.e., \$67.50 / 95). High producing rangeland of 2,000 lbs. DM per acre per year will require only 4.75 acres to support one head. In this case the annual per acre profitability is \$14.22 (i.e., \$67.50 / 4.75). The relationship between annual average per cow profitability (\$67.50) and annual average per cow forage DM requirements (9,492 lbs.) yields a constant relationship indicating that each lb of forage DM is equal to \$0.007111 in ranch profits. This average profitability figure per lb of forage DM production is used to project the profitability of all California rangelands. The model used to estimate the forage DM production for each pixel of California rangeland is described in the following section.

The modeling methodology that was developed to estimate forage production for all California rangelands used forage production estimates from the California State Soil Geographic Database (STATSGO) (Schwarz and Alexander 1995). The forage production estimates were then translated into a livestock carrying capacity for the land and combined with the average per cow profitability (**Table 2-5**) to estimate the average annual opportunity cost of afforestation for each pixel of rangelands on the map. The present value of the annual opportunity cost for every year over the time interval was then calculated using a 4% real discount rate.

2.3.5.1.1 Methodology for estimating forage production

STATSGO provides estimates of forage production (in pounds per acre per year) for each soil component within each map-unit polygon. Using forage production estimates for the dominant soils component in each map polygon (as indicated by the 'comppct' field in the database), a map was produced. This analysis resulted in a map showing forage production ranging from 0 to 5400 lbs/ac.yr for selected parts of the state –about 22% of the state. Because this map covered only 22% of the state, a model was used to extrapolate these values out to the areas not surveyed (**Figure 2-24**). This was done by comparing the biophysical characteristics of the surveyed areas and assigning the same forage production to areas with similar characteristics. The model used the same factors as those used in the forest suitability model discussed earlier (**Table 2-3**). Included in the factor set are mean annual temperature and precipitation, that are two of the most important factors to consider when predicting generalized rangeland productivity (George et al. 2001).

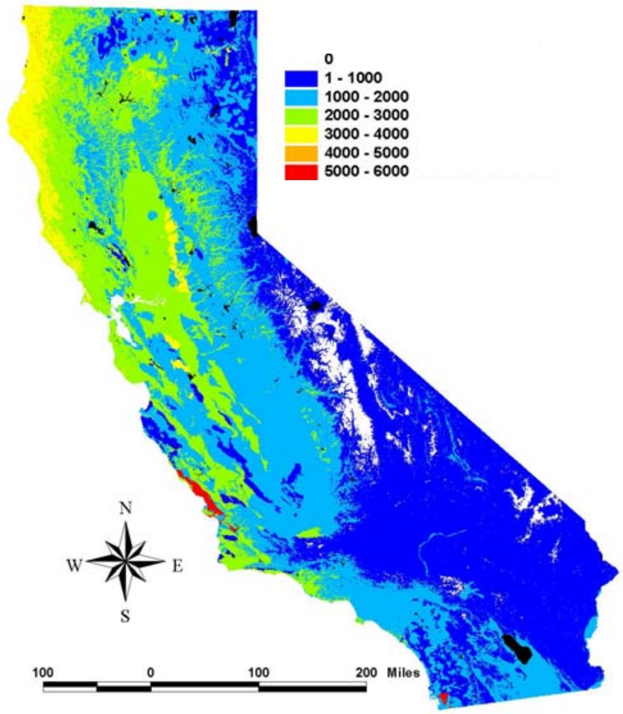

Figure 2-24. Results of multivariate regression for forage productivity across *all land-cover classes*, in pounds per acre per year. Black areas represent water bodies. [NOTE: To convert from lbs/acre per year to t/ha per year divide by 906.9.]

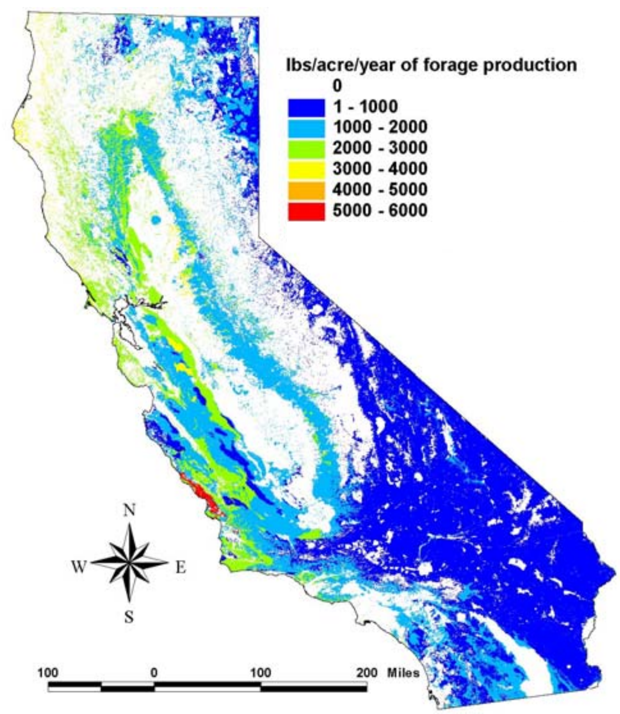

Figure 2-25. Results of multivariate regression for forage productivity *across rangeland classes only*, in pounds per acre per year. [NOTE: To convert from lbs/acre per year to t/ha per year divide by 906.9.]

Empirical locations of forest WHR-types were used to map suitability for forest growth as described in detail above. For mapping forest suitability all that is tracked are the simple statistics about how many forested pixels are present in a class of the factor maps. This method could not be used for modeling forage production because the few actual values of production available needed to be preserved and extrapolated throughout the state. Thus, another approach was necessary. Using the factor set to extrapolate forage production values out to the un-mapped 78% of the state, two modeling methods were tested. The two methodologies were the "category weighted average" approach and a multi-variant regression approach.

To validate the output maps from the two approaches, a sampling of points was laid out across the map used for calibration and the modeled maps. Thus, at each point, it was possible to compare the predicted forage production in the areas where actual forage production data existed. The performance of the two modeling approaches can be seen in relation to the 1:1 line (or perfect prediction). The intercept is forced through zero to illustrate their comparative proximity to a perfect prediction (**Figure 2-26**).

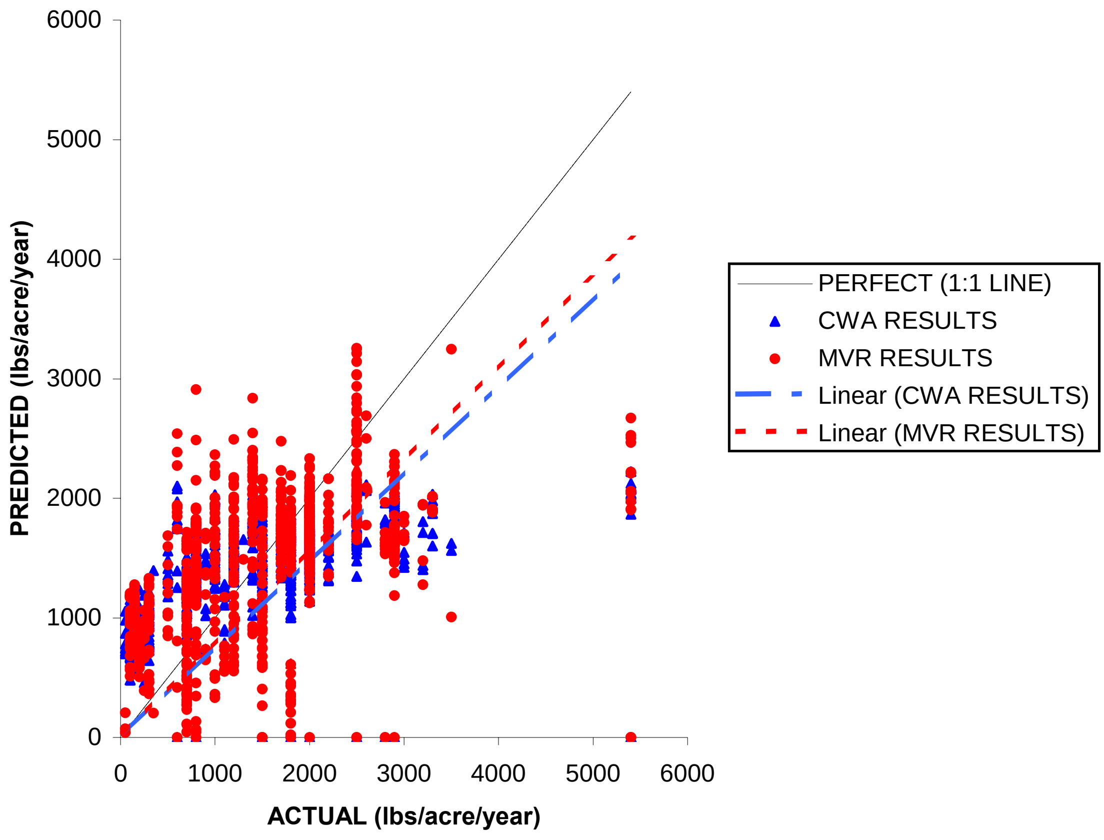

Figure 2-26. Two forage production-modeling approaches: category-weighted approach (CWA) and multi-variant regression approach (MVR). [NOTE: Trend lines were forced through zero.]

In **Figure 2-26**, the regression line for the sample points from the multi-variant regression model is somewhat closer to the 1:1 line than the regression line from the samples from the category-weighted average modeling approach. Based on this validation, the multi-variant regression method was chosen to model the forage production in areas where no NRCS STATSGO data were available. Using the factor set specified earlier, this multivariate regression produced a highly significant relationship in every one of its parameters and it explained 44% of the variance within the sample set. To further verify the model results, the resultant map was compared to county-level cattle populations taken from the National Agricultural Statistics Service. A highly significant positive relationship between cattle population and average forage production for the counties (from the model) was obtained providing further confidence that our model produces realistic estimates.

When comparing current rangeland WHR-types with the forage production map produced by the model, oak woodlands, shrubs and natural and planted grass classes occurred mostly in the areas with higher forage production. Desert shrub, brush and scrub with juniper and Joshua tree WHR-types occurred more often in the lower-production areas (**Figure 2-27**).

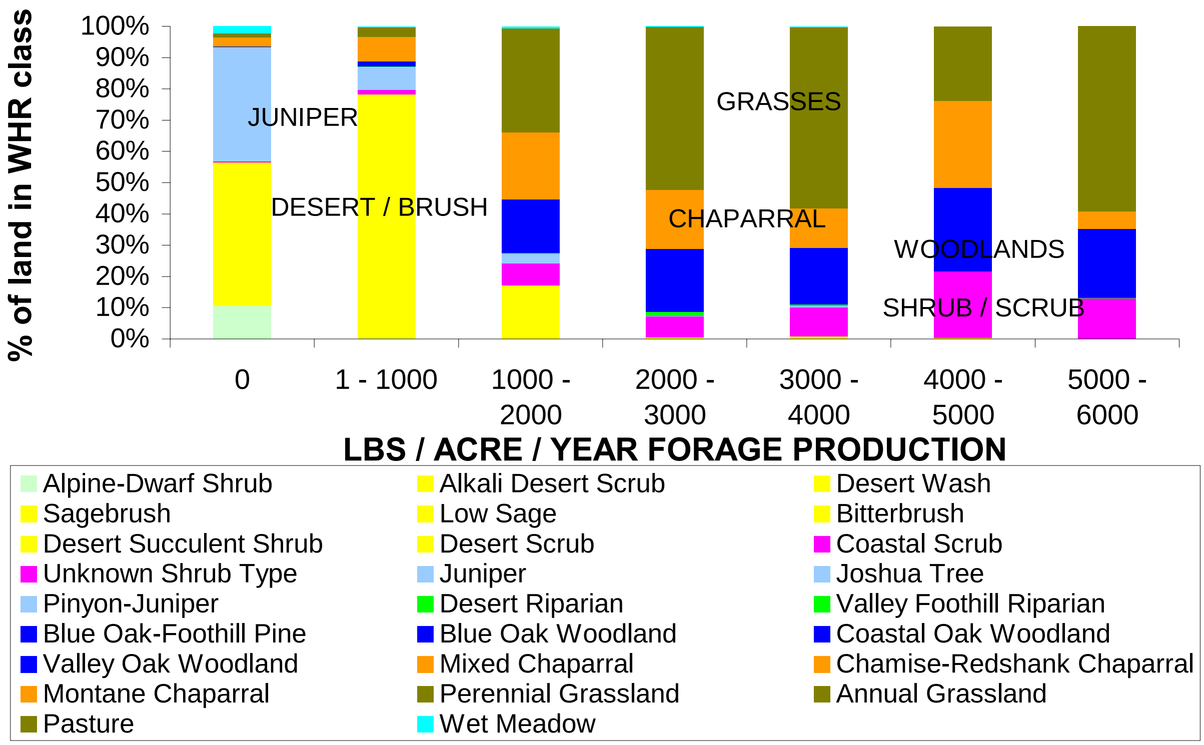

Figure 2-27. Frequency of WHR classes by forage production potential.

2.3.5.2. Conversion costs

Conversion costs represent the estimated cost for establishing tree plantings on rangelands in California. Based on information from the companies in the California timber industry, the costs of establishing forests varies from $300 to $600 per acre. The variability stems mostly from the moisture, soil texture, and slope of the site (E. Murphy 2003, Inventory Forester, Sierra Pacific Industries, Redding, California, pers. comm.). For this analysis, we have used an average figure of $450 per acre.

2.3.5.3. Measurement and monitoring (M&M) costs

This category represents the costs of measuring and monitoring the carbon production over the life of the activity. The M&M costs associated with carbon production contracts is estimated to be about $2.5 per hectare per year on average based on Winrock's experience with measuring and monitoring many afforestation activities throughout the US. Several factors affect the magnitude of the cost including which pools are measured and monitored (in this case we assume only aboveground biomass), frequency of monitoring (once every five years over duration of project), area, and whether the lands are contiguous or dispersed (assumed here to be contiguous). The area of the activity is an important factor and economies of scale exist for M&M costs; therefore, per-hectare M&M costs may be significantly higher for smaller activities. The present value of these costs is calculated over the life of the carbon activity (20, 40, or 80 years).

2.3.5.4. Maintenance costs

It is expected that maintenance costs will be incurred for a period of 5 years from the beginning of the activities to ensure that enough tree seedlings survive to generate a well-stocked stand. Activities expected (depending upon local conditions) include replanting seedlings that died, weeding (or herbicide application), possibly fertilizing and adequate fencing to control livestock incursion until the trees get established. Annual maintenance costs are estimated to be approximately $20/ha.yr during the first 5 years of the activities.

(See, also, Sections 2.6.5 and 2.6.6. for additional factors to examine when analyzing maintenance costs –i.e., fire suppression activities and/or risk evaluation)

2.3.5.5. Total costs

To estimate the total costs of producing carbon on California rangelands, the conversion and land management costs are combined with the present value of the M&M and opportunity costs over the life of the activities. In our economic model, we have included the possibility of contracting costs related to carbon activities. However, because so little is currently known regarding the future structure of carbon contracts, these costs are currently assumed to be zero.

For every parcel of suitable rangeland, the total cost of producing carbon through afforestation is estimated. The costs per ton of carbon produced are then calculated based upon the estimates of carbon sequestered for each specific parcel. These results are aggregated to create carbon supply curves for afforestation of California rangeland. The carbon supply curves are discussed in the following section.

2.4. Results

Using the modeling methodology, a selected set of driver maps was used to perform an analysis of forest-suitability across the state. The results show the geographic areas most suitable for forest growth. Using extensive literature reviews and an analysis of existing forest species in the various suitability classes, estimates of the present carbon stocks on candidate rangelands and the potential additional carbon accumulation on these rangelands yielded maps of their net potential carbon gain. A similar methodology was used to map estimated forage production across the state's rangeland areas. Economic analyses yielded expected opportunity costs as a function of each pixel's forage production potential ranching profitability in the state. These opportunity costs combined with other activity's implementation costs (described above), were used to produce a map of overall carbon activities costs. By dividing the estimated present value of the total cost of carbon production by the net potential carbon gain at a given pixel on the map it is possible to estimate the cost of carbon in the cell in dollars per ton, as depicted in the following equation.

$$\frac{\left(\$/ha\right)}{\left(tC/ha\right)} = \$/tC$$

Where,

- Total cost is expressed in dollars per hectare ($/ha).
- Net potential carbon accumulation is expressed in tons of carbon per hectare (t C/ha).
- Estimated cost of carbon is expressed in dollars per ton of carbon ($/t C).

It is assumed that the landowners will be willing to produce and sell carbon credits if the price paid for these credits is greater than the present value of the stream of costs incurred in producing them. Plotting out the cumulative amounts of carbon credits produced at the various prices produces a carbon supply curve. Carbon supply curves have been produced for 20, 40, and 80-year carbon activities on California rangelands. The maps of estimated carbon prices are shown in **Figure 2-28**. The carbon supply curves are presented in **Figure 2-29**. **Figure 2-30** shows the amount of land producing carbon for the estimated carbon prices.

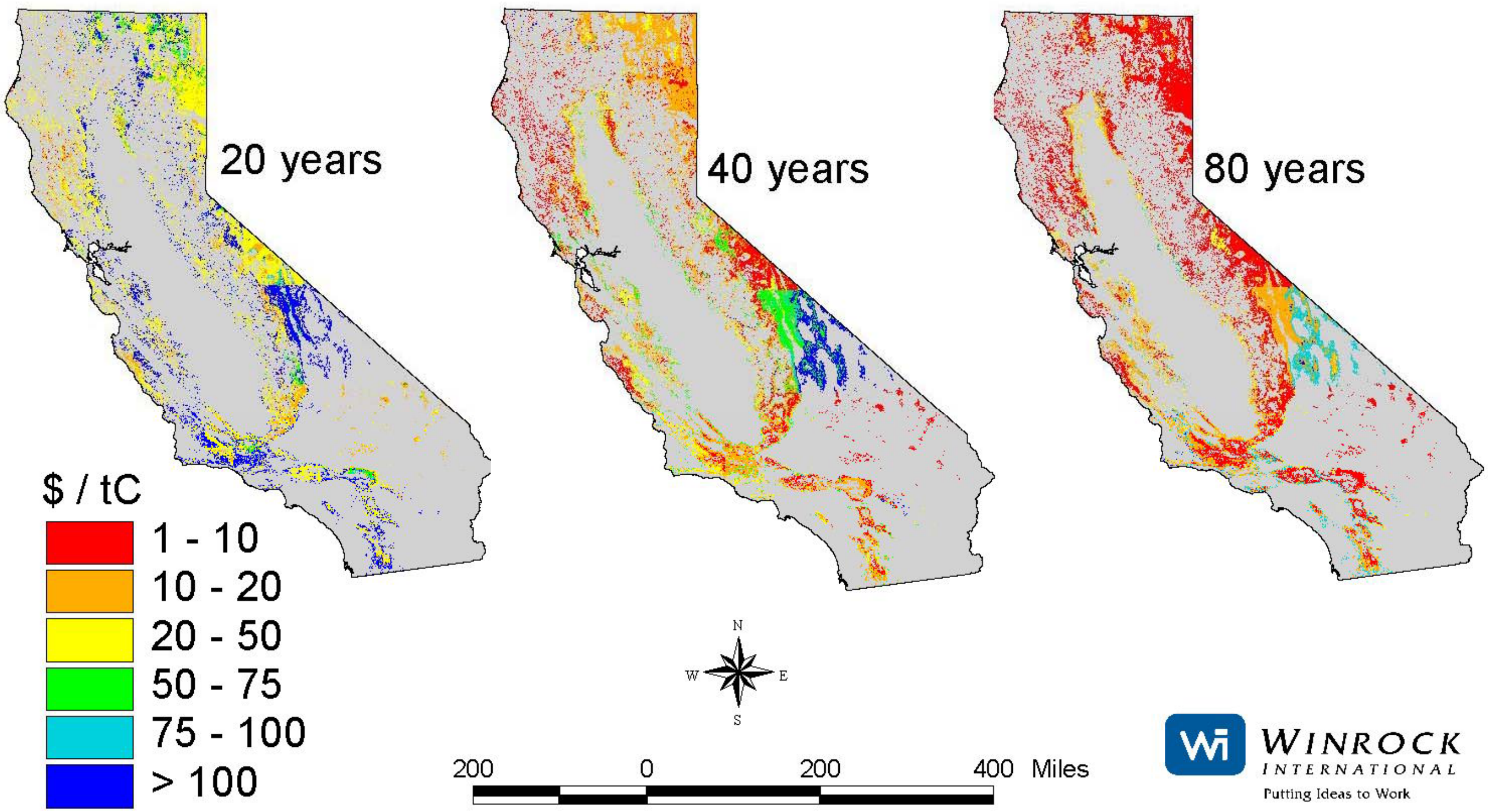

Figure 2-28. Cost of carbon sequestration through afforestation of California rangelands (100 meter grid cells). To convert to $/metric t CO_2, divide by 3.6.

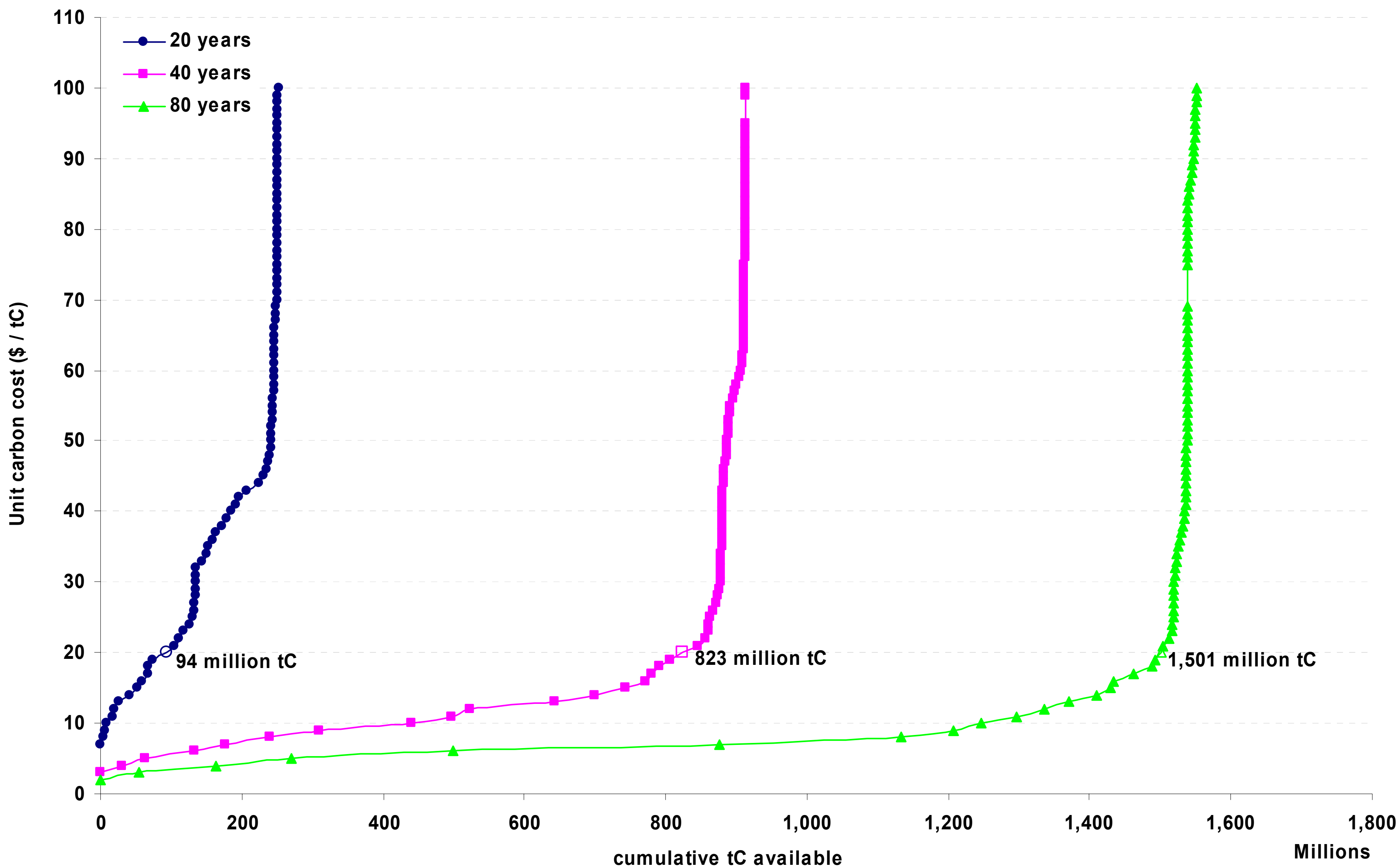

Figure 2-29. Carbon supply curves for afforestation activities on candidate rangelands at 20, 40 and 80 years. To convert to $/metric t CO_2, divide by 3.6.

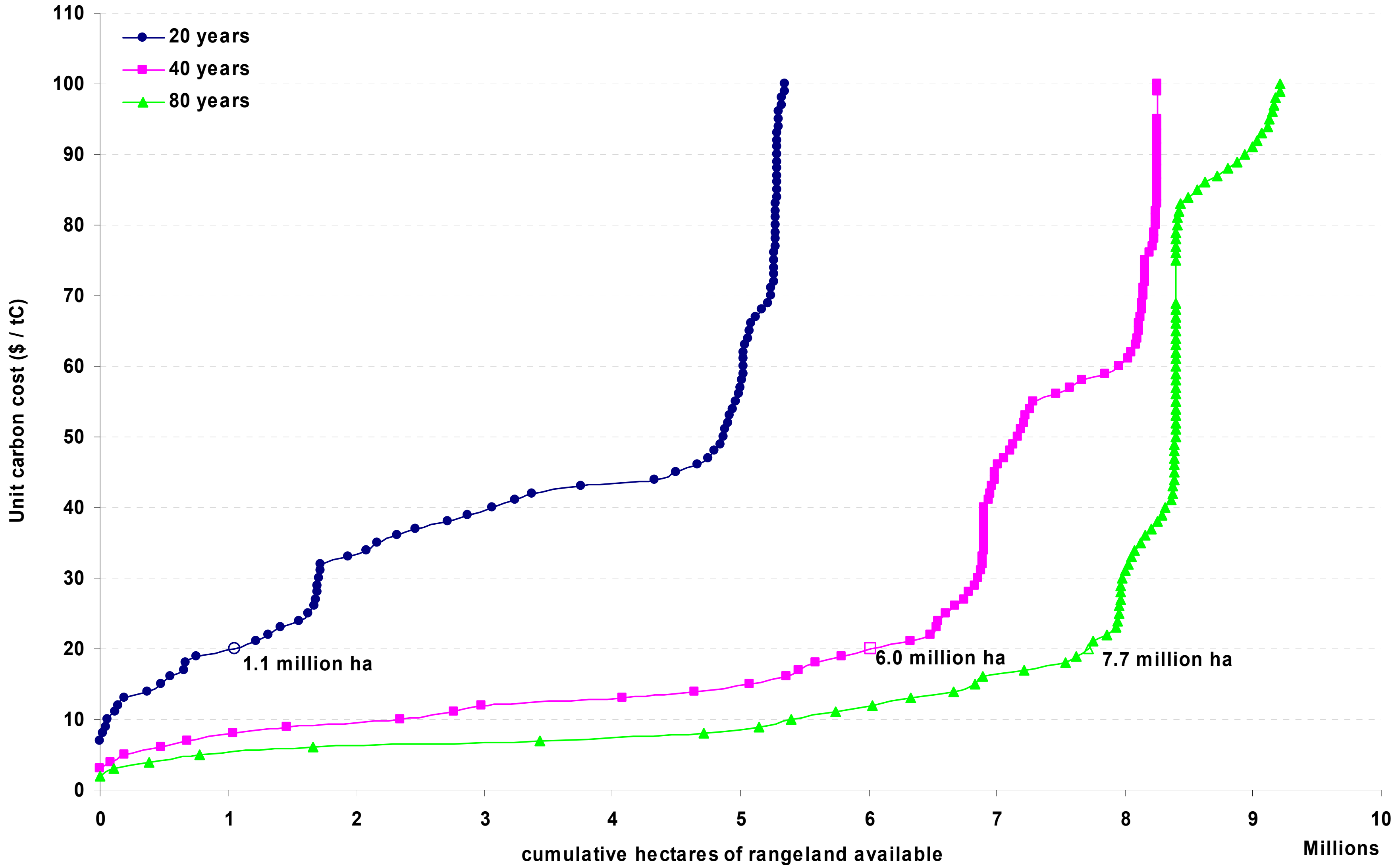

Figure 2-30. Land supply curves for afforestation activities on candidate rangelands of varying $/t C values. To convert to $/metric t CO_2, divide by 3.6.

Generally, the cost per ton of carbon produced is greater for the shorter time periods (20 year) and less for the longer time periods (80 year). The primary reasons for this result include the influence of the economic discount rate used in calculating the present value cost of carbon (the longer the time period the greater effect discounting has on the costs) and the rate of carbon accumulation over time (the longer the duration the greater the change in carbon stock).

As discussed in the previous sections, the real discount rate reflects the time value of money after accounting for inflation. Essentially $1 today is worth more than $1 in 20 years, which is worth more than $1 in 80 years. The real discount rate of 4% used in this analysis implies that $1 in 20 years has a present value of $0.45 and $1 in 80 years has a present value of just $0.04. From this we can conclude that a stream of costs associated with carbon activities is heavily discounted as we move further into the future.

Based on the most suitable tree species for any given site, the average annual rate of carbon accumulation on afforested rangeland over time is greatest for 40-year activities (20.6 million tons per year), followed by 80-year activities (18.8 million tons). The lowest annual rate of carbon accumulation is associated with 20-year activities (4.7 million tons) (**Figure 2-31**).

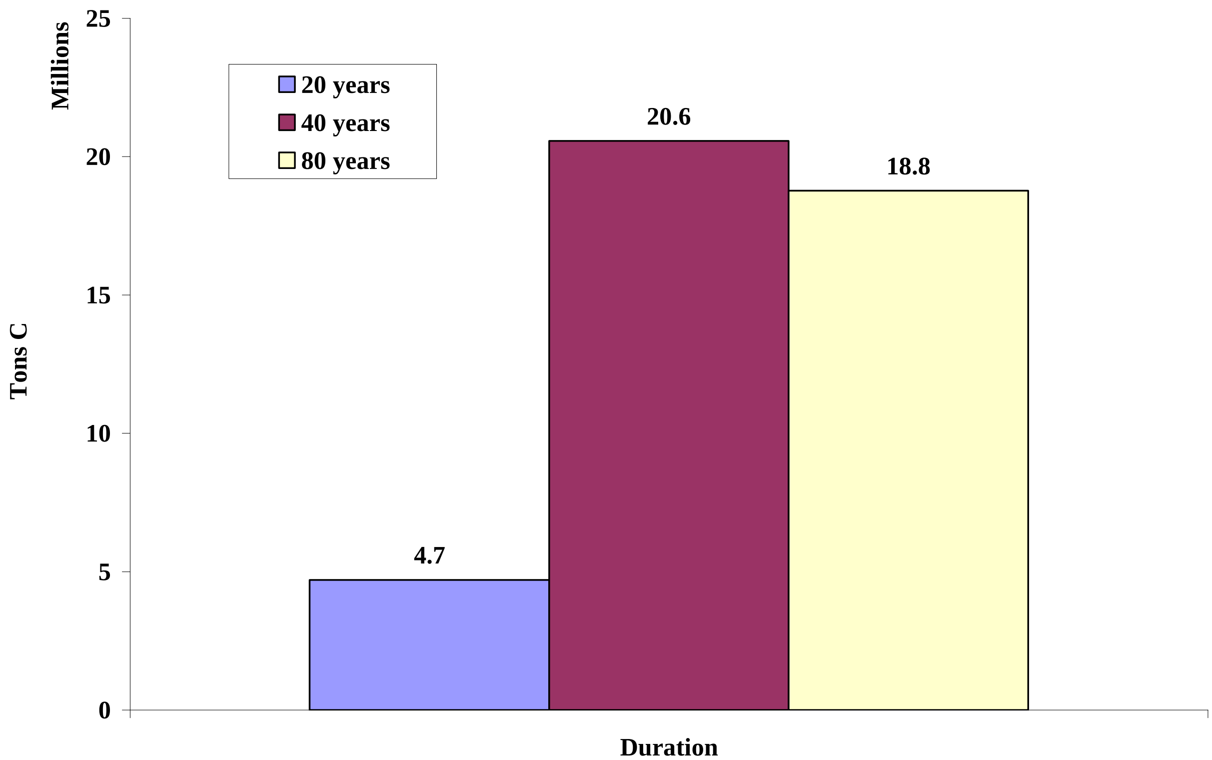

Figure 2-31. Average annual carbon accumulation across potential 20, 40 and 80-year time periods for $20/t C or less ($5.5/metric t CO_2).

The slower rate of carbon accumulation in the first 20 years combined with less future discounting and fewer years over which to spread the initial costs to forest conversion results in higher costs associated with producing carbon for 20 year time periods.

Over 20-years, the total amount of carbon that could be sequestered through afforestation of California rangelands is estimated to be 268 million tons on 7.8 million hectares of land. While much of this carbon would be prohibitively expensive, there are 1.1 million hectares of rangeland that could produce 94 million tons of carbon at $20 or less per ton. This represents 14% of the total suitable rangeland. This percentage of rangeland that could produce carbon for $20/ton or less increases with the length of the carbon activity (**Table 2-6**).

Table 2-6. Quantity of carbon and area of rangeland associated with cost of up to $20 per ton C or $5.5/metric t CO_2.

Life of Activity	Carbon Supplied (million tons)	Rangeland (million ha)	Percentage of Suitable Rangeland
20	94	1.1	14%
40	823	6	68%
80	1,501	7.7	83%

The maps in **Figures 2-32 and 2-33** show where the cheapest carbon credits are likely to be for 20-year activities. The results are shown as area-weighted averages by administrative units of California (counties and generalized ownership classes). Also shown is the proportion of the unit's land that is in candidacy for an afforestation activities (as explained in Section 2.3.4.2) and the total carbon estimated to be available for sequestration (at all costs). **Figures 2-34 through 2-37** show similar results for 40- and 80-year activities.

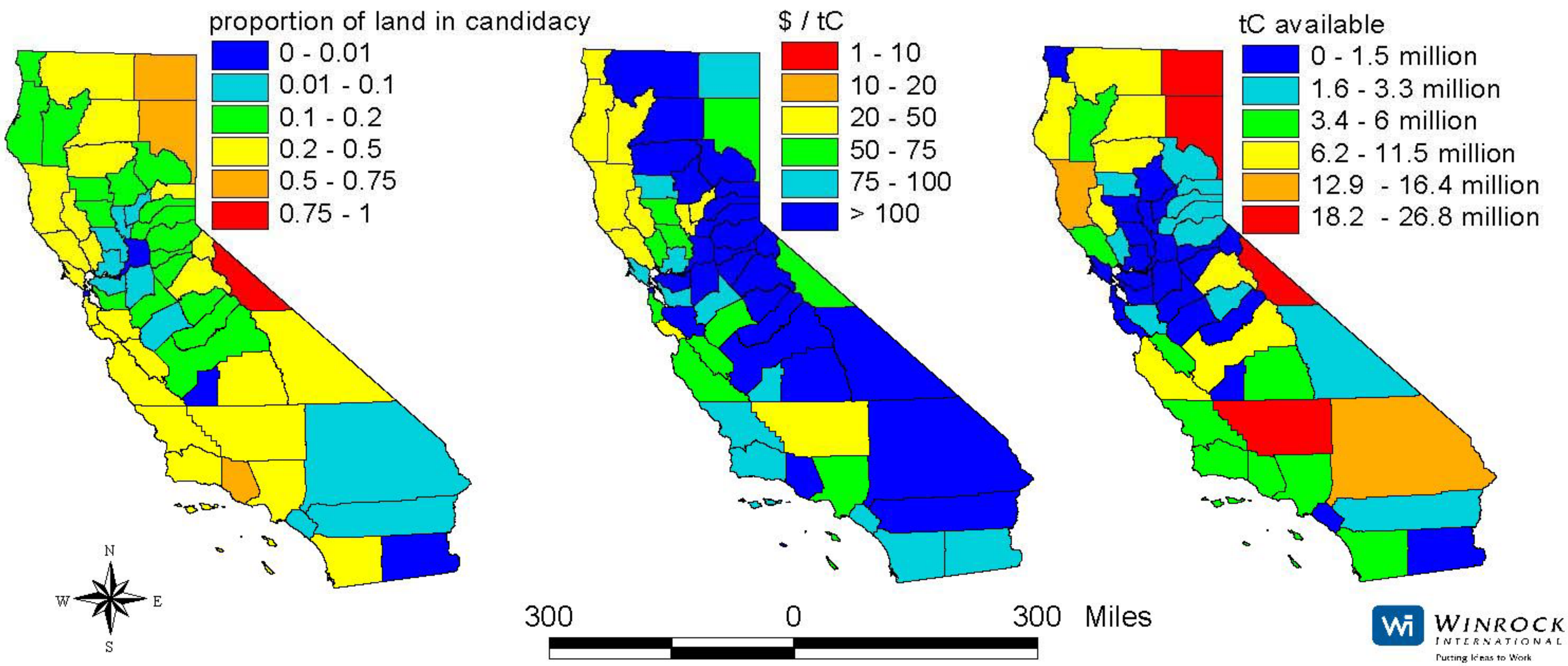

Figure 2-32. Summaries by county of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after <u>20</u> years. Red counties are those with the highest proportion of land, the most carbon and at the lowest cost.

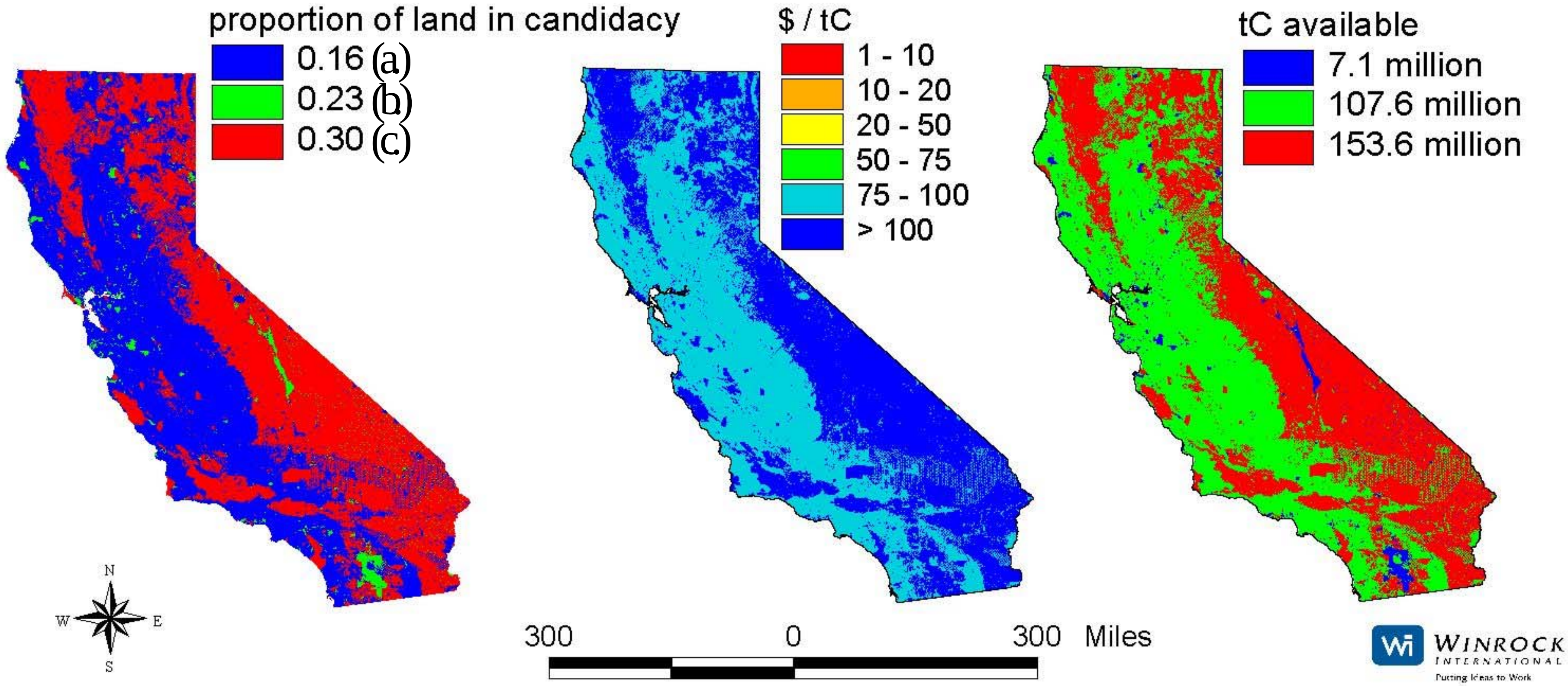

Figure 2-33. Summaries by ownership class of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after 20 years. Ownership classes are, a. "private," b. "public-non-federal," and c. "public-federal."

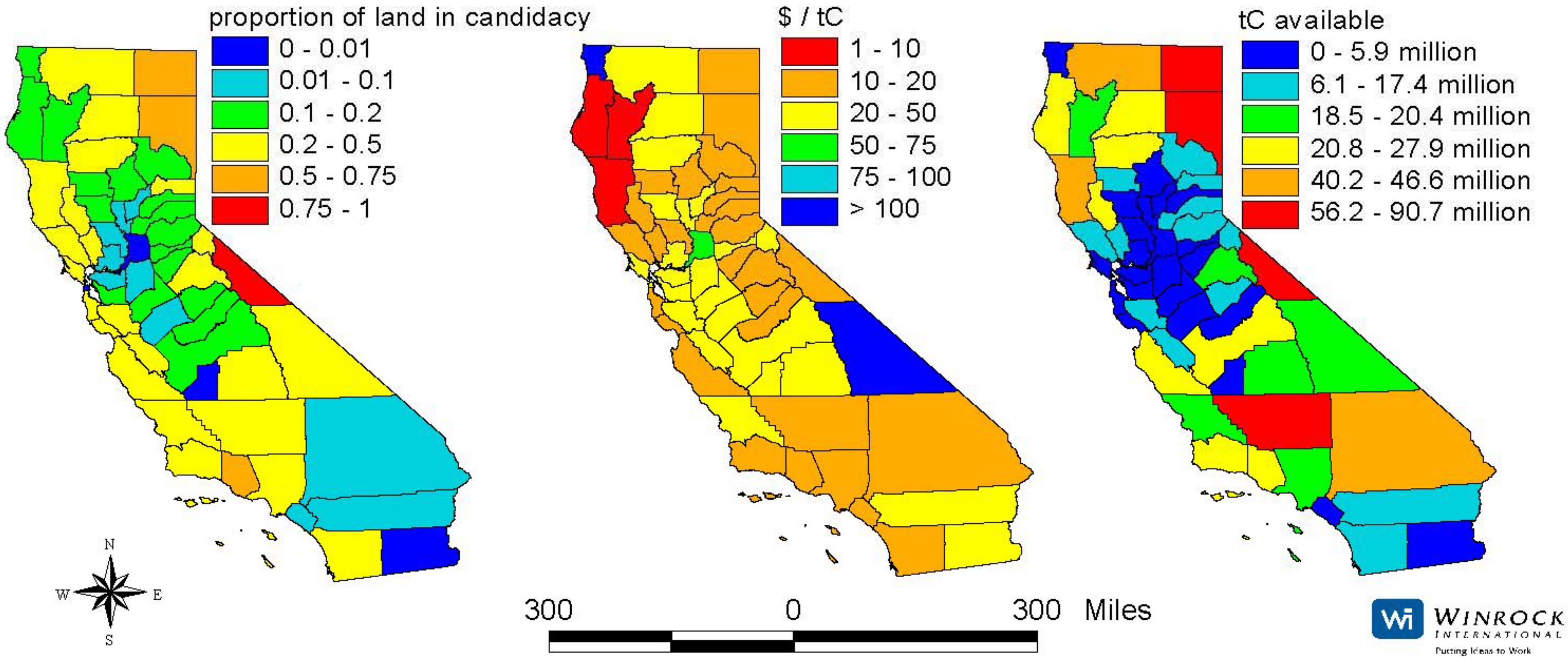

Figure 2-34. Summaries by county of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after 40 years. Red counties are those with the highest proportion of land, the lowest cost carbon, and the most carbon.

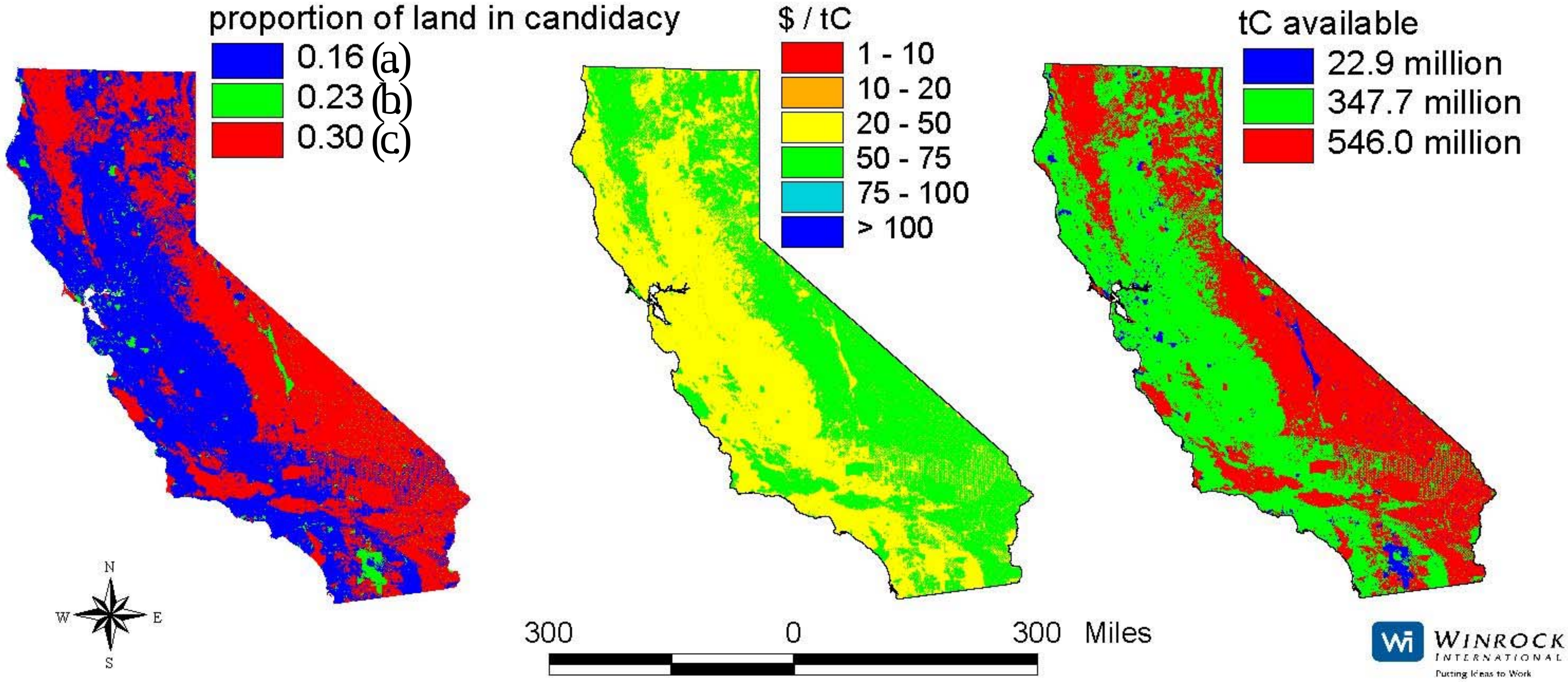

Figure 2-35. Summaries by ownership class of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after 40 years. Ownership classes are, a. "private," b. "public-non-federal," and c. "public-federal."

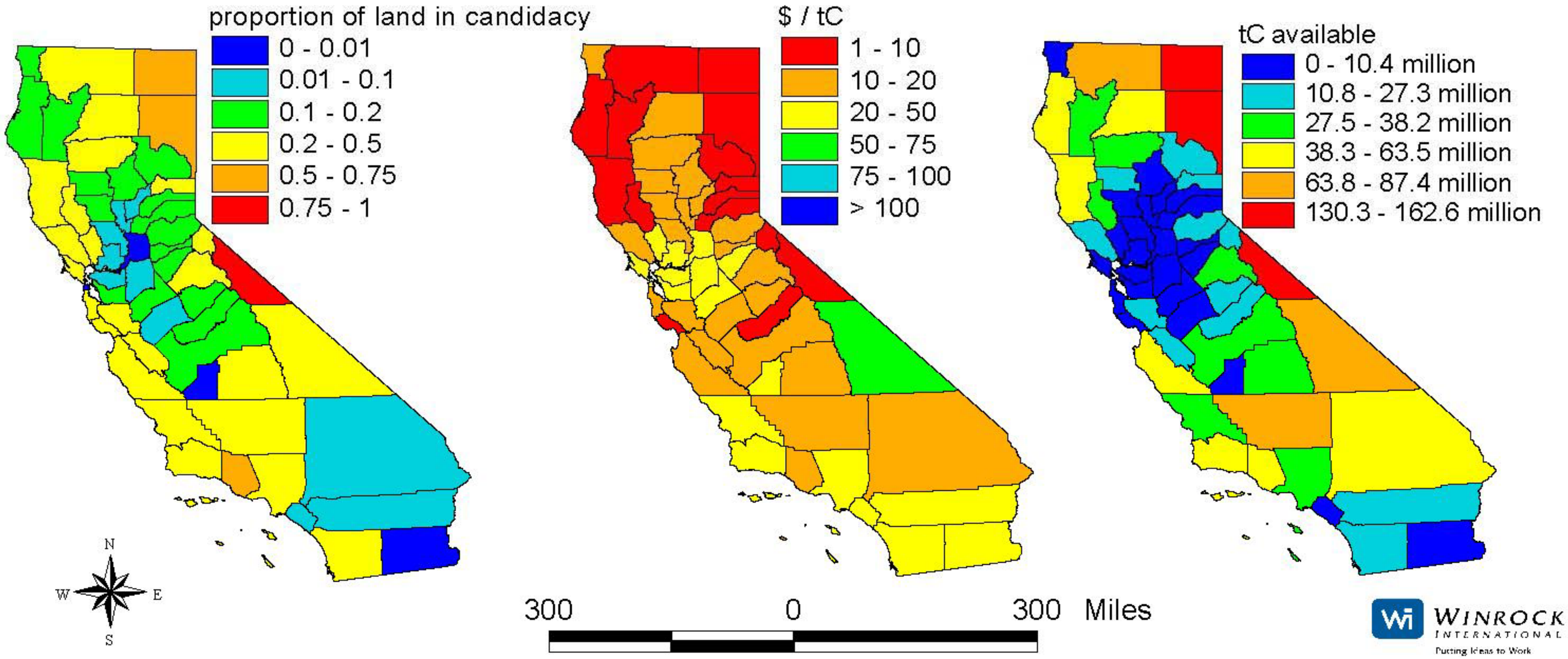

Figure 2-36. Summaries by county of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after 80 years. Red counties are those with the highest proportion of land, the most carbon, and at the lowest cost.

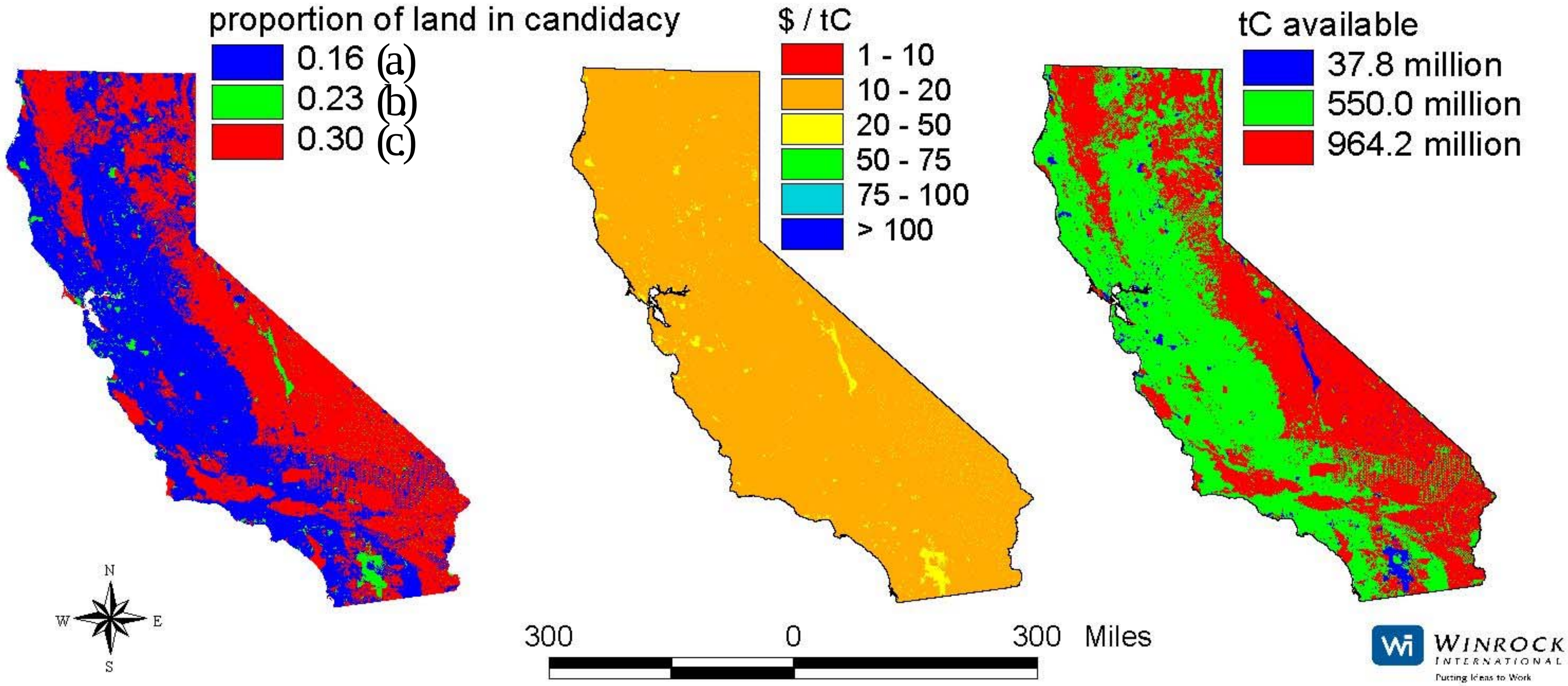

Figure 2-37. Summaries by ownership class of (from left to right) proportion of afforestable rangeland, area-weighted average cost per ton of carbon (to convert to $/ metric t CO_2, divide by 3.6) and total carbon sequestered after 80 years. Ownership classes are, a. "private," b. "public-non-federal," and c. "public-federal."

The areas with the least expensive carbon after 20 years are the North coast counties of Del Norte, Humboldt, Mendocino, Lake, Sonoma and Santa Cruz and the North Central counties of Yuba and Sutter. In the south, Kern County also offers a comparatively low average cost. However, of all of these, Kern and Mendocino were the only counties that offered more than 15 million total tons of carbon after 20 years (Kern offered the most).

For 40-year time periods, the total amount of carbon that could be sequestered is estimated to be 916 million tons on 8.8 million hectares of land. It is estimated that 823 million tons of carbon could be produced for $20 or less per ton, which represents 6 million hectares or 68% of the total suitable rangeland. For carbon prices between $22 and $100 per ton, very little additional carbon will be supplied to the market, as is represented by the near vertical portion of the supply curve. The map in **Figure 2-34** shows the counties where the cheapest carbon credits are likely to be for 40-year activities. The areas with the least expensive carbon after 40 years are Humboldt, Trinity and Mendocino Counties who all offer an average cost per ton of carbon under $10. Twenty-eight counties offer an average cost per ton of carbon between $10 and $20 and of these, Modoc, Lassen, Mono and Kern Counties all reside within the highest category of total carbon tons available (over 56.2 million t C) when Humboldt, Trinity and Mendocino do not.

After 80 years, the total amount of carbon that could be sequestered is estimated to be 1.5 billion tons on 9.2 million hectares of land. It is estimated that 1,501 million tons of carbon could be produced for $20 or less per ton, which represents 7.8 million hectares or 83% of the total suitable rangeland. For carbon prices between $22 and $100 per ton, very little additional carbon will be supplied to the market. The map in **Figure 2-36** shows the counties where the cheapest carbon credits are likely to be after 80 years. The areas with the least expensive carbon after 80 years are fifteen counties, that all offer average carbon values of less than $10 per ton of carbon. Of these counties, only Modoc, Lassen and Mono offer more than 130 million tons of carbon, though.

To calculate net potential carbon gain on an afforested site, the model considered the baseline carbon stocks and the potential carbon accumulation. At times, the baseline carbon stocks were greater than the modeled carbon accumulation. Most notably, this happened before the 20-year point. Therefore, for years after the 20-year point, some new candidates areas appear due to slower initial carbon accumulation in certain areas. The same goes for after the 40-year point. This phenomenon is most evident in the slower-growing desert woodland areas identified as the most dominant woody WHR species in the Inyo County-Mojave and Inyo County-Sierra county-bio-region units ("Pinyon-Juniper," "Juniper," and "Desert Riparian" WHR-types). These species often do not start accumulating any considerable biomass until after 20 years (0.86 t C/ha after 20 years –see **Figure 2-21**). At the 40 and 80-year points, the introduction of these lower-carbon areas into the statewide calculations of carbon supply curves may increase the overall cost of carbon reported for a given administrative unit although it increases the total carbon that could be sequestered as well.

2.5. Discussion

2.5.1. Suitability of Sites for Tree Growth

As a result of the relative coarseness of the data (see above), suitability for growth of certain tree species on a given site cannot be interpreted to mean that every parcel of land in a given grid cell is suitable. Instead, it should mean that on the average, the areas within the grid cells, +/- 1 cell, are suitable. The same is true for interpretation of the forage production model for opportunity cost estimations. In addition, sometimes, the variables used to model suitability have themselves been altered as a result of historical land-use change and the estimates of forest suitability that they reflect might understate the actual potential found across the state. For example, low available water content in the soils, might be a result of the systematic removal of native tree species in an area, or, the introduction of an invasive species like salt cedar (tamarisk). Some studies suggest that if considerable effort is made to gradually prepare a site for introduction (or reintroduction) of forest species, once they were established, factors such as available water content or precipitation would respond (Egan 1996; S. Morse 2003, College of the Atlantic, Bar Harbor, ME, pers. comm.). Sites mapped as completely unsuitable for forest growth may actually be so degraded that conventionally acceptable levels of seedling mortality might need to be reconsidered. In other cases, simply replanting trees may not suffice to restore the ecosystem but more advanced levels of intervention may be necessary possibly including a phased approach. Certainly, the fact that almost all of California's rivers are currently dammed and fed into water distribution systems has a dramatic influence on the present suitability of lands to support their native ecosystems (Veirs and Oppler, 1995). These issues bring to the attention several reasons why the suitability mapping in this study could *under*-represent tree growth suitability.

Several California researchers have gone so far as to suggest that the natural succession of some chaparral ecosystems is to oak woodlands (Callaway and D'Antonio 1991; Wells 1962; Sampson 1944). If the huge expanses of chaparral-dominated ecosystems in California are actually in an intermediary state of vegetation, the assumption can be made that given a proper foothold, much of it would become denser woodland, or even forest ecosystems.

By investigating historical patterns in the settlement of California and the exploitation of its natural resources inferences can be made about the pre-settlement state of California's forestlands and the underrepresentation of forest suitability as presented in this research. Several relevant points from S. D. Veirs and P. A. Oppler's section on California from the book *Status and Trends of the Nation's Biological Resources* from the National Biological Service (1995) are presented below to further illustrate the historical facts about California settlement's effects on its native vegetation:

- The number of Native Americans at the time of European or European American contact is estimated to be approximately 300,000. The staple food of the people of the Central Valley was meal made from valley oak acorns. Nearly 2/3 of that population died as a result of diseases brought by Spanish Franciscan missionaries in the late 1700s.
- Mexico ceded California to the United States of America in 1848 and large influxes of gold prospectors and settlers began arriving via the Oregon trail and other cross-country land-routes. The European American population increased from 15,000 in 1848 to

380,000 in 1860. The current population of California is estimated to be 34 million people.

- By the late 1800s intense logging of California's forests fueled the state's construction, mining, railroad and foreign timber export industries (**Figures 2-38 through 2-42**).

Figure 2-38. California redwood harvest. Photo: Union Lumber Company Collection. Note man in lower right (from Andrews 1956).

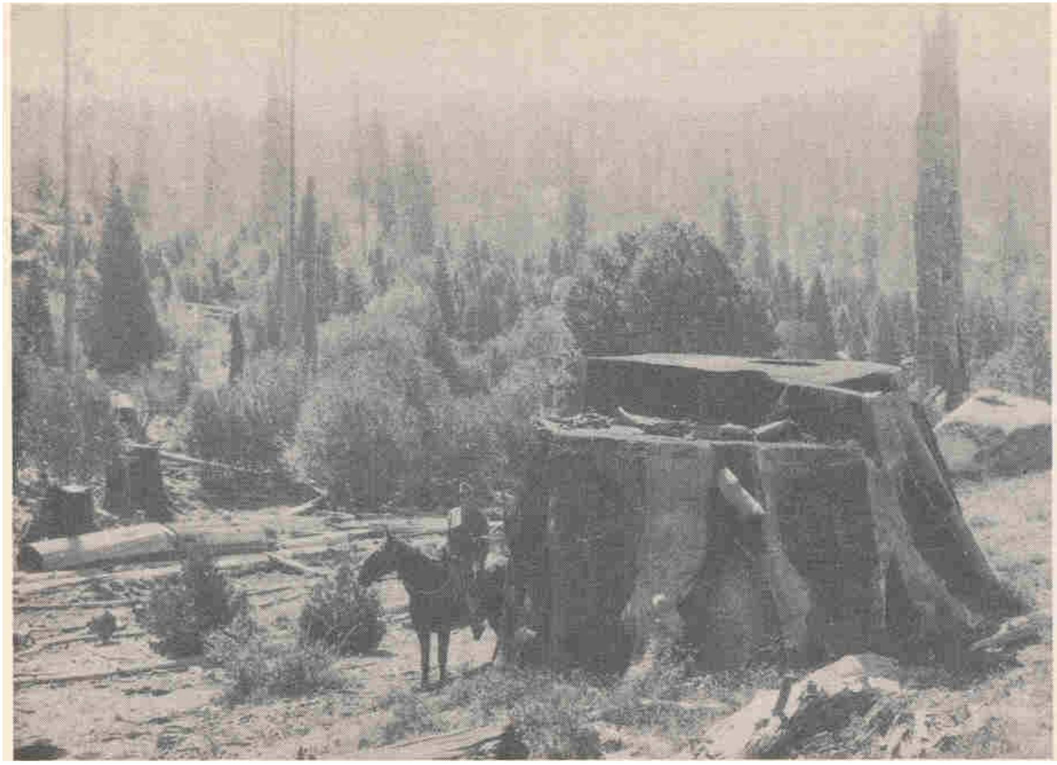

Figure 2-39. Photo: H.E. Roberts (from Andrews 1956)

Figure 2-40. Photo: Union Lumber Company Collection (from Andrews 1956)

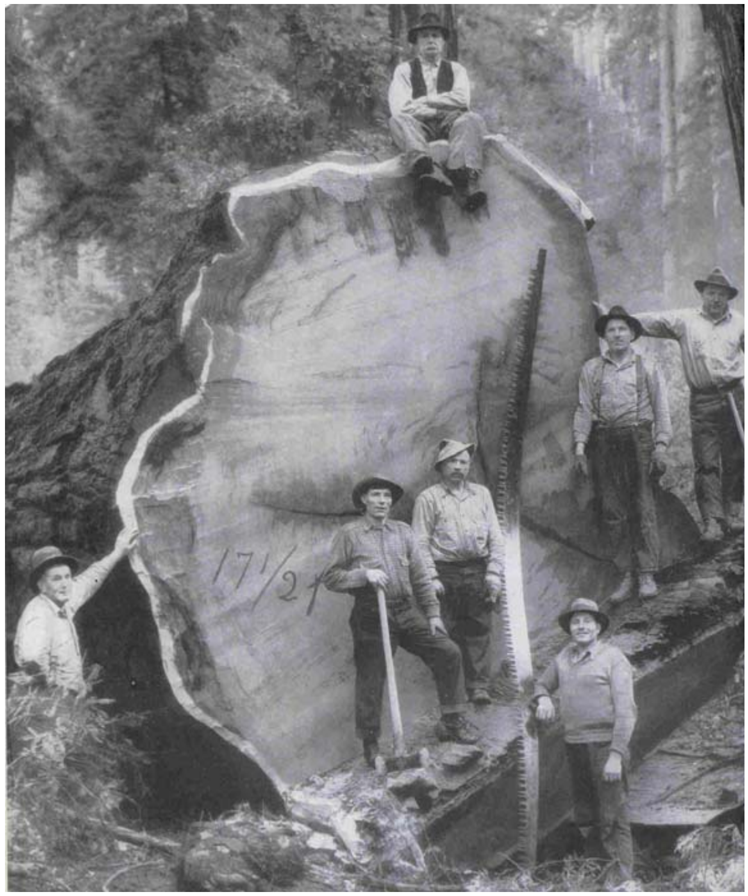

Figure 2-41. Photo: Union Lumber Company Collection (from Andrews 1956)

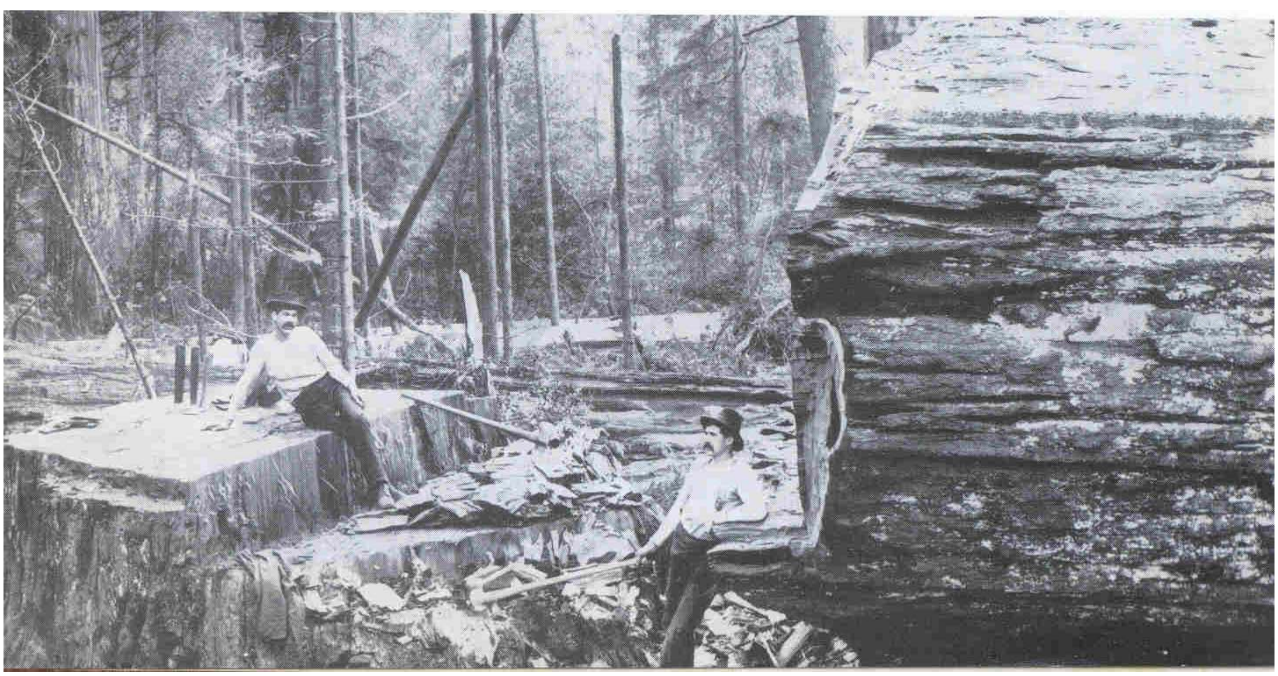

Figure 2-42. Photo: Hammond Lumber Company Collection (from Andrews 1956)

Concerns about the decimation of the natural landscapes of California led to the U.S. Congress' creation of Yosemite State Park in 1864, Sequoia and Yosemite National Parks in 1890 and the formation of the Sierra Club by John Muir in 1892. After World War II the need for timber in California again boomed and it is estimated that between 1950 and 1975 annual production of timber in the state was at 5.3 billion board feet.

2.5.2. Soil Types

Different soil types were initially considered in the analysis of forest suitability although they were eventually discarded as factors. Their inclusion was considered due to concerns raised by several California scientists who indicated that serpentine soils, in particular, often exhibited high water capacity in areas of high precipitation and that they were often *not* suitable for forest growth (L. Myer 2003, Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, pers. comm.; Christopher Hipkin 2003, College of Natural Resources, University of California-Berkeley, pers. comm.). Other reports indicate that forests on serpentine soils may tend to be either completely absent or noticeably more open than on non-serpentine soils –notably in the areas of ancient volcanism (Veirs and Oppler 1995).

In response to these concerns, analysis of the areas mapped as dominantly serpentine soils by STATSGO yielded the following types in small areas in the locations shown in **Figure 2-43**.

- Mollic Palexeralfs, Clayey-Skeletal, Serpentinitic, Frigid;
- Ultic Haploxeralfs, Clayey-Skeletal, Serpentinitic, Mesic;
- Lithic Argixerolls, Clayey-Skeletal, Serpentinitic, Thermic;
- Lithic Haploxerolls, Loamy-Skeletal, Serpentinitic, Mesic;
- Lithic Argixerolls, Clayey-Skeletal, Serpentinitic, Mesic.

Figure 2-43. Serpentine soils in California as mapped by STATSGO dominant soil components.

Surprisingly, though, when comparing these serpentine soils areas to areas mapped as forest WHR classes by CDF-FRAP, on the average, 69% of the areas were forested. In fact, it is estimated that forests cover most of the serpentine soils in the Klamath Mountains of northern California (Alexander, E.B. 1994). Also, when examining the STATSGO-mapped locations of serpentine soils, it can be expected that as little as 40% of those areas may actually be serpentine soils due to the fact that the minimum mapping unit for STATSGO is much greater than the largest areas of serpentine soil outcrops (E. Alexander 2003, Soils and GeoEcological Investigations, Concord, California, pers. comm.). Thus, even if it was proven that some serpentine soil presence resulted in a lower suitability for forest growth, at the large scale of analysis for which STATSGO was intended and for which is needed by this study, serpentine soil outcrops could not be accurately detected. Additionally, being that serpentine soils are often too thin to hold moisture (Veirs and Oppler 1995), the use of the soil available water content data layer in the model should capture any adverse effects on tree suitability from the presence of this soil type. Therefore, to model and map forest suitability, areas of serpentine or other specific soil types were left out.

2.5.3. Ecoregions and historical vegetation maps

Several ecologists have modeled and mapped potential vegetation and biological strata in the USA (Lugo et al. 1999; Bailey et al. 1994; Küchler 1964) and, also, several maps of historical forest distribution in California exist that have been brought into GIS format through digitizing. A model was considered that would map forest suitability by combining these inputs of historical information and ecological models to map areas suitable for forest growth. In the same manner as with the first forest suitability model, forest suitability was mapped using the qualitative factor maps listed in **Table 2-7** (shown in **Appendix D**) to gauge potential vegetation or ecosystem types.

Table 2-7. Datasets used in alternate modeling approach.

Data	Source
Küchler's potential vegetation map of California	Küchler 1964 & Tang et al. 2003
Holdridge Lifezones map of the USA	Lugo et al. 1999
Bailey's Ecosystems map of the USA	Bailey et al. 1994
1934 California Vegetation map (Calveg34)	USFS
1945 California Timber map	USFS
1977 California Vegetation map (Calveg77)	CDF-FRAP

The two methodologies were identical and both used empirical information of existing forests for calibration. Data in this second factor set used distributions of forests from only as far back as 1934 and ecological models based, in-part, on involuntarily subjective ideas as to where forests should exist that may have also be based on datasets from this century. It was decided that the first methodology using biophysical factors would be used instead of this one as a result of those concerns.

2.6. Future Steps

2.6.1. Analysis of Ecological Effects of Afforestation of Rangelands

Restoration of biological diversity and water resources is a possible additional benefit that could accrue from afforestation of existing rangelands. In addition to carbon sequestration, these co-benefits could be achieved through incentives to land owners. The sale of carbon credits is one such incentive. Similar incentives could be offered for the creation of biodiversity, wildlife habitat, water quality, etc. on rangelands.

Freilich et al. (2003) lists several possible ecological benefits from a shift from grazing activities on rangelands to afforestation. Ideas for indicators could be derived from such a list:

1. Reintroduction of native carnivores and other "problem animals" into the food chain.
2. Turn the tide of the present truncation of the food web through the elimination of carrion for scavenger species and decomposition biomass in ecosystem carbon cycles.
3. Habitat defragmentation by increased contiguity of forested landscapes and reduction in fencing and, possibly road networks.
4. Reduction of exotic weed presence in range ecosystems and in the toxic chemicals used to control them.
5. Positive impacts on water supplies and riparian habitats.

Policies can be designed to reward the creation of these public goods as co-benefits related to carbon sequestration activities. Additional incentive mechanisms can be created to enhance the payment from potential future carbon offset markets. Quantification and valuation of these co-benefits are an important area of future research related to these activities.

In addition to the positive benefits that afforestation of rangelands could have, there are potential risks involved, also. By replacing grazing lands with forests, there is a risk that some of the existing rangelands could harbor rare and endangered herbaceous and shrub species. Future analyses at a finer scale could contribute to enhanced understanding of this effect. For instance, obtaining data layers that depict the ranges of such species and overlaying them with the rangeland carbon supply maps would indicate prohibitive areas for afforestation.

2.6.2. Effects of Urbanization on Opportunity Costs of Rangelands

An alternative to afforestation of rangelands is conversion to urban development, as mentioned above. The basis for this suggestion is that urban growth is projected to occur in rangeland areas. Landis and Reilly (2003) concluded that projected urban growth is a significant threat to grazing lands in Riverside, Placer, San Diego, and San Bernardino counties; a moderate threat in Orange, Ventura, Alameda, Solano, Sacramento, Los Angeles, Santa Cruz, and Santa Barbara counties; and a minor threat elsewhere in the state.

The total additional area of rangelands projected to be converted to urban use by 2020 is 77,600 ha and by 2050 is 216,300 ha. These areas represent 1.6% and 2.7% of the total area of rangeland available for afforestation up to a cost of $100/t C for the 20 year and 40 year time periods, respectively. Moreover, for the four counties where urbanization is a significant threat, the average cost of carbon is more than $75-100/t C over 20 years (**Figure 2-32**) suggesting that, over this time frame, this high cost would likely discourage conversion to forests anyhow. However, over a 40-year time frame, the cost for converting rangelands to forests for most of the counties is $10-20/t C (**Figure 2-34**), thus converting to urban areas may be more competitive depending on the price of real estate. For these reasons (small land area affected and/or high cost for carbon sequestration), we believe that future analysis of the effects of opportunity cost due to urbanization on the carbon supply of rangelands may not be warranted.

2.6.3. Reductions in Cattle Populations and Consequent Effects on GHG Emissions

If landowners elect to afforest their rangelands in response to new policies, a consequence of decreasing the area of grazed rangelands could be a decrease in the number of cattle. Cows are responsible for a significant proportion of the non-CO_2 greenhouse gases produced globally. For example ruminant livestock produce 22 % of the global methane emissions from human-related activities (RLEP 2004a).

Consequently a decreased number of cows could lead to a net GHG benefit. (However, for this to be a genuine benefit there must be no leakage. In other words the decrease in one location because of this activity must not lead to an increase elsewhere to fulfill the demand.)

From enteric fermentation, each non-dairy cow produces:

80 kg CH_4/year (RLEP 2004b)

= 1,840 kg CO_2eq/yr

From manure and urine deposition each non-dairy cow produces:

2 kg CH_4/yr (IPCC 1996)

= 46 kg CO_2eq/yr

1.4 kg N_2O/yr (IPCC 1996)

= 414 kg CO_2eq/yr

So for the reduction of each head of cattle on rangelands in California, 2.3 t CO_2eq emissions would be avoided per year. For afforestation of rangelands, not only would the carbon benefits arise from the increase in carbon stocks of the trees but there would also be additional GHG benefits from the elimination of cattle. This would result in even cheaper carbon credits. More detailed analyses at a finer scale where information on likely head of cattle that would be eliminated by converting rangelands to forests is needed to fully factor in this effect on the carbon supply.

2.6.4. Changes in Rangelands Management

This study recognizes that historical patterns in land-use change have transformed California's natural landscape and diminished its carbon sequestration capacity. Timber extraction, development and the ranching industry have caused an increase in the area of the rangeland land-cover classes.

While afforestation of suitable rangelands may increase carbon stocks, changes in rangeland management may be able to increase carbon sequestration while improving the profitability of California ranching. If this proves to be true, the opportunity cost of changing rangeland management to sequester carbon could be negative, thus reducing the cost of supplying carbon credits. This section discusses the issues related to improving rangeland productivity as a potential class of a carbon activity.

Further analysis of the costs and benefits of improved rangeland management as a source of carbon credits should be performed. It has been recognized that a holistic management approach to ranching, that includes management-intensive grazing, may offer practical ways to develop a clear and focused vision for future rangeland use that allows planning on how to do so in the most economically, environmentally and socially sound way (Savory 1988; Murphy1994; Voisin1959).

Management-intensive grazing (MIG) is an alternative forage production strategy that can be used to reduce livestock production costs. It is a system in which the animals graze one section (paddock) of a larger pasture for a short period of time, often 12 or 24 hours for dairy cows and 1 to 3 days for beef cattle in humid climates. The size of the paddocks are controlled so that the stocking rate is high enough to reduce selective grazing and require that most of the forage is harvested by the animals. The animals are rotated through the paddocks allowing previously grazed paddocks to regrow to an optimal level for nutrient yield before regrazing. Longer rest periods are necessary in arid climates. This method is also known as rotational, intensive-rotational, or short duration grazing. The French agronomist Andre Voisin first described the scientific principles underlying MIG in the late 1950s (Murphy 1994; Voisin 1959). While the intensity of paddock rotations can be much greater in humid regions, a less intensive rotation can also improve rangeland productivity in arid regions.

2.6.4.1. Increasing Soil Carbon with MIG

Research has shown that conventional grazing increases the rate of soil organic carbon (SOC) accumulation compared to mechanical harvesting. Lovell et al. (1997) measured an increase in SOC of 1.2 to 1.4 t/ha.year over the first three years of grazing versus mechanical harvesting. The increase is due to increased stubble after grazing, fresh manure deposits (60 to 95 % of ingested nutrients), and hoof action that incorporate manure into the soil. Because MIG uses higher stocking rates than conventional grazing, it has been shown to further increase SOC. Stuedemann et al. (1998) measured an increase in SOC of 2.7 kg/ha over three years for each additional grazing day (an animal unit per hectare per day). Higher stocking densities enhance the breakdown of surface litter and the incorporation of nutrients into the soil, which helps to improve grass productivity. Improved productivity is a key to increasing C storage (Schnabel et al. 2001).

A small but increasing percentage of livestock farmers is adopting MIG (primarily in the humid regions) because it has the potential to increase farm profitability. Therefore, the opportunity costs associated with improving management practices on grazing land will generally be small or negative. Some additional infrastructure, such as fencing and watering systems, will be required.

2.6.4.2. Improved Productivity Requires Less Land

The use of MIG increases the density of the vegetative sward, which allows more forage to be grazed from the same area. Therefore, the amount of land required for a given herd size decreases when switching from conventional grazing to MIG. For example, if a farm has 1000 hectares of grazing land and only requires the use of 500 hectares to meet its herd requirements after adopting MIG, then the remaining 500 hectares may become available for afforestation activities at a reduced opportunity cost. However, this result will be driven by the livestock market's ability to absorb additional animals at a profitable price.

If the price for livestock is profitable, ranchers may opt to convert all of their land to MIG and increase their herd size and sales. If the price is poor or questionable, farmers may use less land and be willing to produce carbon through afforestation on the remaining land.

2.6.5. Estimating the Risk of Fire

The potential occurrence of fire is probably the largest risk to any carbon sequestration activity in California. Thus, in addition to the costs of physical management of the afforested areas, attention must be paid to the threat of fire to these investments. Prior to tree planting activities, burning may be necessary to clear lands for planting and to reduce fuel loads. After this initial fuel load treatment, certain areas may need special attention over the lifetime of the activity (the carbon purchase contract's lifetime). Models can be developed to estimate the costs of such treatments. A representative from Sierra Pacific Industries (SPI) estimate that costs for fuel load thinning range from $40 to $100 per acre depending on the average slope and proximity to roads at a given site (E. Murphy 2003, Sierra Pacific Industries, Redding, California, pers. comm.).

The CDF-FRAP's Fire Rotation Interval map (**Figure 2-44**) was created from 50 years of fire history maps on land areas that have been grouped according to fire-related factors such as climate, vegetation, and land ownership. The Fire Rotation Interval is the number of years it would take for past fires to burn an area equivalent to the area of a given group. Fire Rotation Interval is calculated by dividing total area of the group by the annual number of acres burned and then dividing into 4 classes.

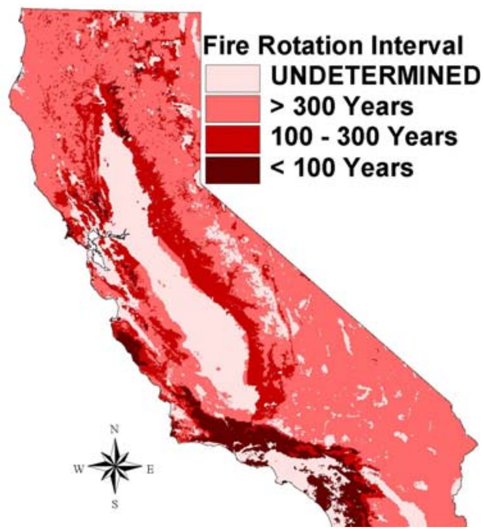

Figure 2-44. Fire rotation interval map provided by the California Department of Forestry – Fire and Range Assessment Program (CDF-FRAP).

Fire Rotation Interval is combined with expected fire behavior (based on fuel load models) in a separate CDF-FRAP analysis to define fire threat. Because it is impossible to estimate what fuel loads will be present at a site after an afforestation activity, only the Fire Rotation Interval map is used for our analysis.

Based on our analyses, it can be seen that the majority of the identified candidate areas for afforestation (49%) fall within the lowest risk category of fire rotation interval (**Table 2-8**). An additional 29% of the lands fall within the 100-300 year fire rotational interval. However, from a cost perspective, the "High" to "Very High" rotation intervals contain potentially some of the least costly carbon credits. Further research on the potential risk to carbon from fires and the costs of fire prevention activities is warranted. Refinements in the Fire Rotation Interval map to define the "Undetermined" areas might also add greater understanding of these phenomena.

Table 2-8. Percentage of candidate cells identified by the model that falls within CDF-FRAP fire rotation interval classes.

Fire rotation interval class description	Years	% of candidate cells	20-year avg $/t C	40-year avg $/t C	80-year avg $/t C
UNDETERMINED	UNDETERMINED	8%	$107.53	$28.14	$14.32
MODERATE	> 300 Years	49%	$120.01	$59.53	$20.25
HIGH	100 - 300 Years	29%	$111.65	$23.16	$15.24
VERY HIGH	< 100 Years	15%	$122.07	$15.97	$22.91

2.6.6. Impacts of Climate Change

A recent report to the California Energy Commission's Public Interest Energy Research Program (CEC 2003) was undertaken to assess the impacts of potential climate change on California. Climate models were used to project changes in climate across the state of California through 2100. Recent analyses of climate models showed that they did not, on average, project California becoming wetter or drier and that no firm conclusion about the future change in the direction of precipitation could be drawn. A dynamic general vegetation model was used to estimate the effects on the distribution and the productivity of terrestrial ecosystems at a scale of 100 km2. The report concluded that under all climate change scenarios, forests and other types of vegetation would migrate to higher elevations as warmer temperatures make those areas more suitable for survival. The report also estimated that if it gets wetter, forests would expand in northern California. On the other hand, if it got drier areas of grasslands would increase across the state. What these changes would mean for afforested areas in today's rangelands is unknown but worthy of further investigation; the effect would most like be relevant to those lands where afforestation was planned to extend up to 80 years or more, the period over which the cheapest carbon is produced.

2.7. References

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3.0 AGRICULTURAL LAND

3.1. Introduction

Agricultural production has major impacts on global carbon (C) pools and fluxes. The processes of land clearing, draining, sod breaking, cultivating, and fertilization have all served to dramatically reduce the store of C in soils (Lal et al. 1998). Agriculture is both a source and a sink for atmospheric greenhouse gases (GHG) (EPRI 2004). However, through improved or alternative management practices, agriculture has the potential to become a significant sink, particularly for CO_2 (Lal el al. 1998), relative to current levels. There are several important ways that agriculture can improve its GHG balance. These include increasing carbon sequestration in the soil, offsetting emissions through bio-fuel production, reducing C emissions from eroded sediments, and reducing fuel consumption in the industry.

California is the nation's leading agricultural producing state by far, with greater cash receipts than the second and third leading states (Texas and Iowa, respectively) combined. California is home to eight of the nation's ten top grossing agricultural counties, led by Fresno with nearly $3.5 billion in annual cash receipts from agriculture (California Department of Food and Agriculture 2002).

Agriculture in California is also extremely diverse, with approximately 350 different crops being produced (this includes seeds, flowers, and ornamental plants) on 87,500 farms. The top commodities by value of production for 2000 are listed in **Table 3-1**. California leads the nation in production of more than 70 different crops and livestock products, including many fruits and salad bowl vegetables (California Department of Food and Agriculture 2002).

Table 3-1. California's top 10 commodities by value (year 2000).

Commodity	Value ($1,000)	Rank
Milk and Cream	3,703,920	1
Grapes	2,836,313	2
Nursery plants	2,247,256	3
Lettuce	1,484,115	4
Cattle and calves	1,266,985	5
Tomatoes	951,030	6
Cotton	898,263	7
Flowers	841,914	8
Strawberries	767,306	9
Hay	730,422	10

Source: California Agricultural Resource Directory 2001

According to the USGS, National Land-Cover Dataset (NLCD), approximately 11% of the land area in California is used for crop production. This includes the classes "Row Crops," "Small Grains," "Orchards/Vineyards/Other," "Pasture/Hay" and "Fallow" (USGS 2000). This land is primarily in the Sacramento and San Joaquin Valleys (**Figure 3-1**).

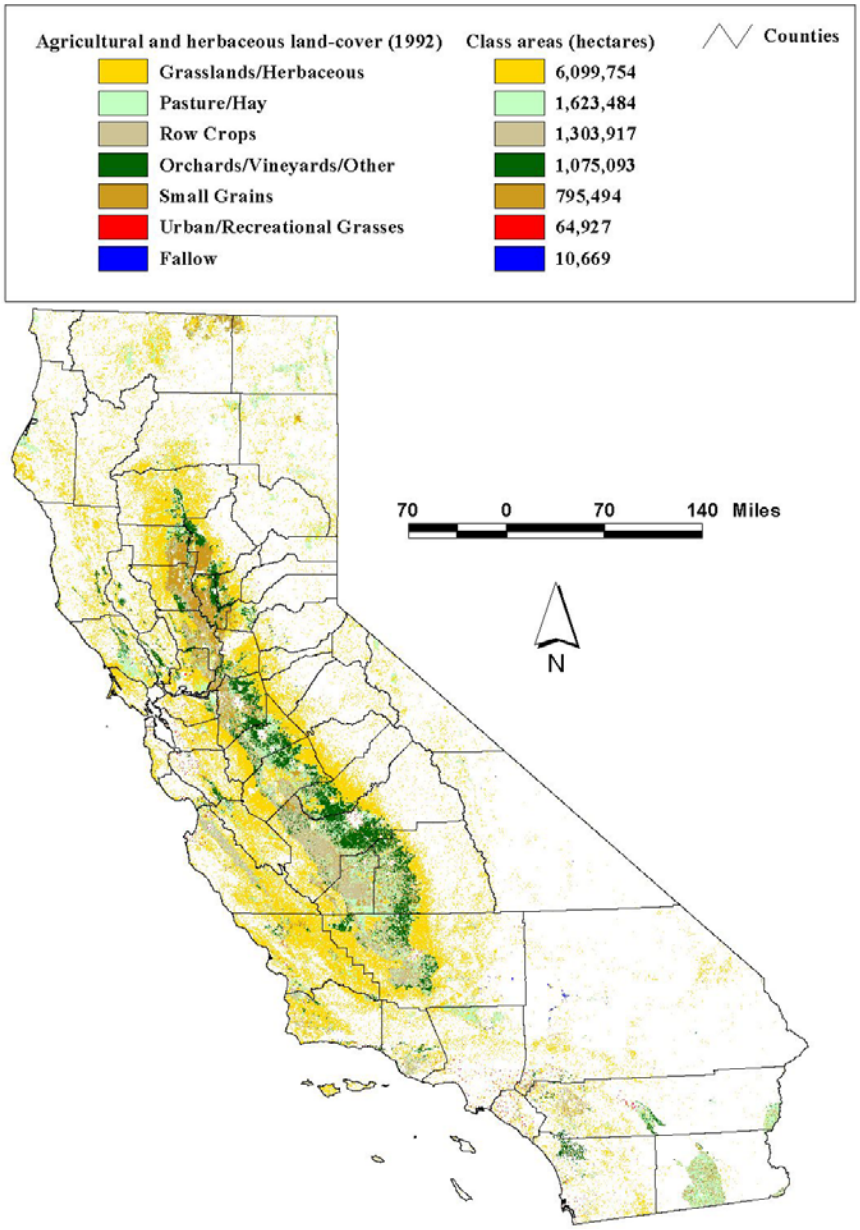

Figure 3-1. Agricultural and herbaceous National Land Cover Dataset classes and land areas in California.

The average market value per hectare for California agricultural land ($7,657) was estimated to be 250% higher than the national average ($2,989) in 2002 (USDA-Economic Research Service 2002). Although high on average, the value of California agricultural land varies and is closely associated with its location relative to population centers and secure access to water for irrigation.

Due to the high productivity and land values associated with California agriculture, the opportunity costs of displacing agricultural production with afforestation is not likely to be a valid source of carbon projects, as is the case in some other regions of the country. However, altering land management strategies, including conservation tillage, may provide appropriate and affordable types of carbon projects for California agricultural land.

3.2. Management practices to increase soil organic carbon

The primary means for agriculture to increase C sequestration is to adopt land management practices that improve and maintain high soil quality (Bezdicek et al. 1996).

Increasing soil organic carbon (SOC) storage has numerous benefits for the soil, agricultural productivity and the environment. It can increase water infiltration and soil fertility, decrease soil erosion and compaction, and improve water quality. California soils are generally low in SOC compared to many other regions of the U.S. This is primarily due to intensive tillage practices and climactic factors (Horwath and Doane 2002).

There are several management practices that have been shown to increase SOC in the California context. These include the use of cover crops, the application of organic wastes to the soil, and the use of conservation tillage (Horwath and Doane 2002). Because California lags most other regions of the country in the use of conservation tillage and cover cropping (Huyck 2002) and has relatively low SOC levels, it has the potential to generate large additional increases in C sequestration. However, because California has little experience with these management strategies, there is very little scientific evidence of how well they will perform in the context of California agriculture. The following sections discuss the use of conservation tillage, which sometimes involves cover crops, and the potential for C sequestration on California agricultural land.

3.2.1. Conservation tillage

Conservation tillage (CT) is a term that represents numerous types of reduced-tillage field practices for crop production that are designed to minimize soil erosion and enhance soil tilth. Eliminating one or more plowing operations characterize the use of CT. The tillage practices that fall under the CT umbrella include strip-till, ridge-till, minimum tillage, no-till, and other practices. California agriculture trails most other regions of the nation in the adoption of CT practices. It is estimated that CT is practiced on less than 1% of cropland in California (Mitchell et al. 1999) compared with 30-50% in some other regions. The primary reasons for this very low level of adoption are the lack of information on using CT with furrow irrigated agriculture (Huyck 2002) and farmers' risk aversion related to the production of high value agricultural crops (Jeff Mitchell, 2004, Conservation Tillage coordinator, UC Davis, Department of Vegetable Crops, pers. comm.).

Each of the different CT practices disturbs the soil to various degrees. Of the CT practices, no-till disturbs the soil the least and, therefore, has the greatest ability to increase carbon sequestration on agricultural lands. Unfortunately, California has extremely limited adoption of no-till agriculture. The use of CT also has the potential to reduce the emissions of fossil-fuel based CO_2 from agriculture by reducing fuel usage through a decreased number of field operations. However, the use of no-till on very wet soils has been estimated to contribute to increased emissions of nitrous oxide that has significantly higher global warming potential than does CO_2 (Li et al. 2004).

3.2.1.1. Carbon sequestration estimates from conservation tillage

In this section, we estimate the amount of carbon that could potentially be sequestered in the soil of land producing row crops and small grains. Unfortunately, there is a dearth of scientific research results on the ability of CT to increase SOC in California agricultural land. One study conducted by University of California researchers has shown that 5MT of additional C was sequestered per hectare over 12 years using CT (Horwath and Doane 2002). This equals 0.42 MT/ha/year of sequestered C. This measurement is very close to the average rate of C sequestration from numerous research studies from around the world that were summarized in West and Post (2002).

Research by USDA has shown that the level of SOC is directly proportional to the amount of soil disturbance (Reicosky 1997). Therefore, no-till will generally result in greater C sequestration levels than will other CT practices involving greater soil disturbance. We have assumed that an average level of C sequestration CT (including the adoption of no-till on some lands) will be 0.48 MT/ha/year for medium textured soils.

Soil texture also affects the rate of C sequestration in agricultural soils. Clay particles present in the soil tend to surround the SOC and protect it from decomposition. Because finer soils have a higher proportion of clay particles, they allow less decomposition of SOC and therefore result in higher rates of C sequestration (Six et al. 2002). This analysis adjusted the estimated C sequestration rates to account for the effect of soil texture. Soil scientists at Pennsylvania State University used STATSGO soils data to create a standardized map of soil layers and their textures across the Coterminous United States (Miller et al. 1998). The assumption was made that for no-till practice, the soil layers that encompassed the top 20 cm of soil should be analyzed. The Penn State soil texture classifications were aggregated across these top-most layers into one of four categories: very fine, fine, coarse, or very coarse. The associated rates of C sequestration are shown in **Table 3-2**. A soils texture map was then created for the entire state using these four categories.

Table 3-2. Estimated C sequestration rates by soil texture class

Texture Class	C sequestration rate (MT/ha/yr)
Very fine	0.61
Fine	0.52
Coarse	0.44
Very coarse	0.35

The next step in our analysis was to apply these C sequestration estimates to applicable agricultural land, according to the soil texture mapping. In theory, conservation tillage has the potential to be applied in the production of any row crop or small grain. In reality, CT is less likely to be applied in the production of high-value and specialty crops (Jeff Mitchell, 2004, Conservation Tillage coordinator, UC Davis, Department of Vegetable Crops, pers. comm.) and more likely to be applied to commodity crops such as corn, cotton, and wheat, and on certain produce crops such as tomatoes. Because spatial representations of statewide land-use data indicating specific crop production are not available, we have applied the estimates in **Table 3-2** to all land listed as producing row crops and small grains in the 1992 NLCD map (USGS 2000).

This information was used as a data layer in a GIS application and combined with the soil texture map, allowing us to apply the soil texture-adjusted C sequestration rate estimate to all row crop and small grain land. By summing across soil texture categories for each map polygon, we were able to estimate the potential C sequestered from the application of CT on all applicable California agricultural land.

The total amount of carbon that could be sequestered from the use of CT on row crops and small grains in California is estimated to be 1.05 million MT per year (3.85 $MMTCO_2$eq.) (**Table 3-3).** It has been shown in numerous studies that C sequestration in soil is slow in the first five years, has the greatest rates in years 6-10, increases at a decreasing rate in years 11-15, and often reaches a steady-state after 15-20 years. These studies are summarized in West and Post (2002).

Table 3-3. Land area (ha) and carbon (t C) potential by texture class.

	Row Crops		Small Grains		Total	
Texture Class	ha	t C	ha	t C	ha	t C
Very Fine	690,899	421,448	437,831	267,077	1,128,730	688,525
Fine	106,654	55,460	127,722	66,415	234,376	121,876
Coarse	7,500	3,300	6,288	2,767	13,788	6,067
Very Coarse	471,001	164,850	198,686	69,540	669,687	234,390
Total	1,276,054	645,059	770,527	405,799	2,046,581	1,050,858

After aggregating to the county-scale, the estimated C sequestration potential on row crop and small grain land can be seen on the map in **Figure 3-2**. The vast majority of this potential is located in the Sacramento and San Joaquin valleys in the central part of the state. Additional smaller pockets can be seen in far northern and far southern counties, as well as along the central coast.

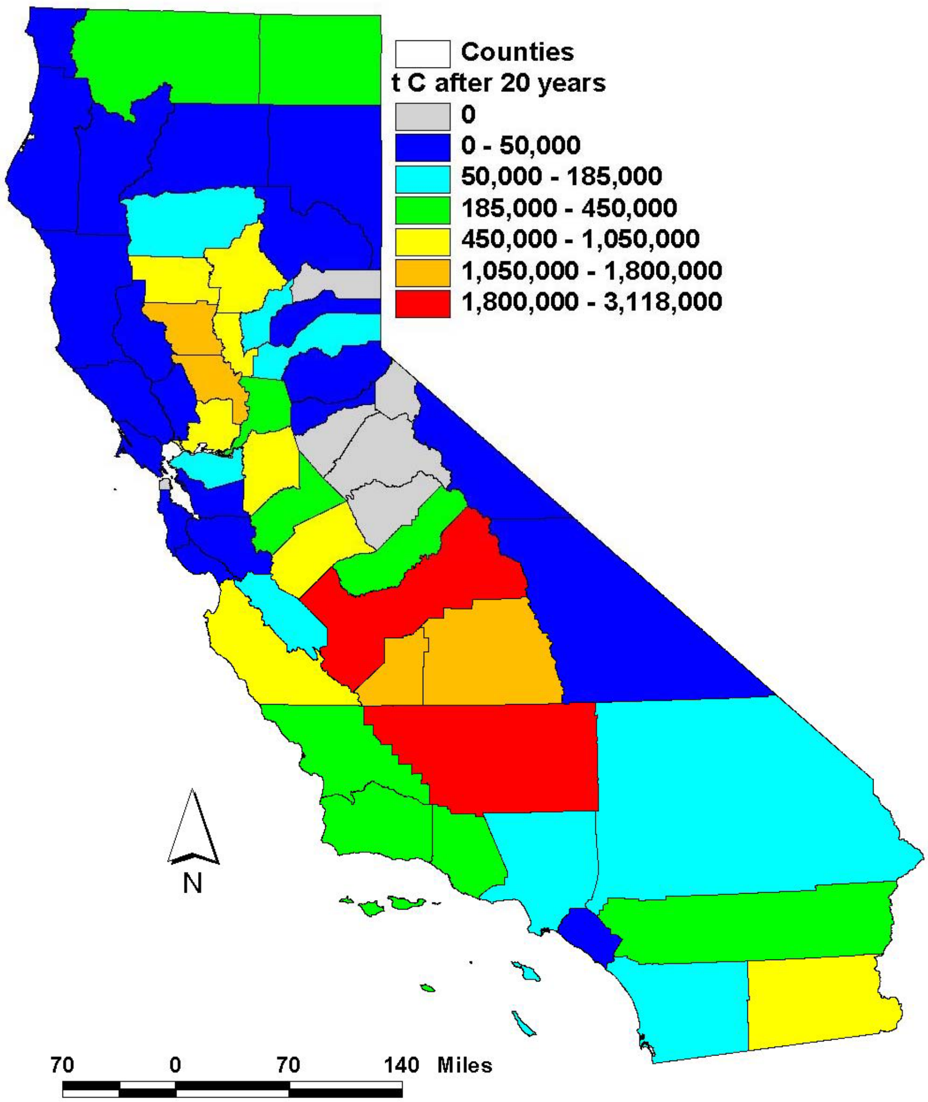

Figure 3-2. Aggregated soil carbon sequestration estimates under conservation tillage regimes on row crops and small grains.

3.2.1.2. Costs associated with conservation tillage

Although CT has been proven to be a profitable management strategy for certain crops in many regions of the country (e.g., Northern Plains, Midwest, South), there are only very limited data regarding its application in California. A study conducted by faculty at UC Davis shows that the economics of CT were generally more favorable when performed in combination with cover cropping for cotton and without cover cropping for tomatoes (Mitchell et al. 2003). This research indicated generally reduced profitability for CT on cotton production and generally increased profitability on tomato production. However, these research results do not indicate statistical significance. Actual economic performance will vary greatly across crops, regions, and over time. To assume that CT will generally increase the profitability of current production systems implies that farmers are not currently maximizing profits. Although this contradicts a core tenet of economic theory, it is possible that the use of CT can increase profitability in some cases.

Given the lack of research data and the great diversity of crops produced, it is essentially impossible to estimate the costs of CT adoption across the state in a spatially explicit manner. As discussed above, CT is likely to increase profitability for some crops and reduce profitability for other crops. Within one crop the impact of CT on profitability may also vary across the state. Some efforts are being made within the UC system to learn more about the profitability of CT for agricultural production. Information on these efforts can be found at http://groups.ucanr.org/ucct/.

In addition to the opportunity cost (i.e., the impact on profitability) of using CT on agricultural land, the costs associated with measuring and monitoring (M&M) C accumulation must be accounted for. From Winrock's experience with M&M projects across the U.S., we have estimated that it costs an average of $3.15/ha.yr to provide adequate M&M services related to changes in tillage practices on agricultural land.

Because the rates of C sequestration resulting from CT are assumed to be in the range of 0.35-0.61 t/ha.yr, it is clear that opportunity cost of using CT must be quite low for this class of projects to produce C at competitive costs. Based on an average rate of 0.48 t/ha.yr, to produce C at $20 or less per ton will require that the opportunity cost of using CT be no more than $6.45/ha.yr ($20 * 0.48 - $3.15). In places where the use of CT increases profitability by more than the M&M costs, C can be produced at no net cost. Such instances represent potentially very inexpensive C and/or significant windfall for farmers who produce and sell additional C.

3.2.1.3. Additional considerations

The use of CT on agricultural land is likely to have some significant associated environmental co-benefits. These include water quality benefits from reduced soil erosion, air quality benefits from reduced machinery use and tillage, and possibly the provision of wildlife habitat for some species in some seasons. The potential of producing multiple public environmental benefits simultaneously and selling them as "stacked" credits may provide additional incentives for landowners to alter current land management strategies, resulting in additional C sequestration.

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Appendix A

Value of Aging Timber with Alternative Carbon Calculation

Appendix B

Quantitative Driver Maps

Appendix C

Factor Map Details

Appendix D

Qualitative Driver Maps